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The Evaluation of High Molecular Weight Methacrylate as a Treatment Option for Shrinkage Cracks in Airfield Pavement

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THE EVALUATION OF HIGH MOLECULAR WEIGHT METHACRYLATE AS A TREATMENT OPTION FOR SHRINKAGE CRACKS

THESIS

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Abstract

Air Force policy dictates that only epoxy can be used as a treatment option for shrinkage cracks in concrete airfield pavement. However, since epoxy is not ideal for shrinkage cracks, this research focuses on the evaluation of high molecular weight methacrylate (HMWM) as a treatment option. Laboratory experiments were performed on four sealants to determine whether they could penetrate a crack 24 inches deep, bond to the concrete, and resist water intrusion. Three HMWMs (TK-2415, Kwik Bond KBP 103, and Castek Transpo T-70) and one epoxy (TK-2110) were assessed. The four sealers were applied to 32 concrete specimens with crack widths varying from 0.2 mm to 1 mm. Dyed water was poured onto the surface and allowed to sit before the concrete specimens were rebroken, at which point the specimens were evaluated to determine where, if any, water penetrated the crack. The Transpo T-70 performed the best by fully penetrating a crack 0.1 mm thick; the TK-2415 penetrated a 0.2-mm crack and the Kwik Bond and TK-2110 both only penetrated a 0.6-mm crack. Beam specimens were also tested in cold weather, with similar results. The Transpo T-70 penetrated a 0.2-mm crack, the TK-2415 penetrated a 0.4-mm crack, and the Kwik Bond and TK-2110 both penetrated a 0.6-mm crack. Evaluating the ability of the sealants to bond to concrete and resist water intrusion was not accomplished because the sealants could not be contained in the specimens. Despite this, the laboratory results suggest that HMWM would be a viable option to treat shrinkage cracks in concrete airfield pavement, which is consistent with the literature.

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Austin R. Hayes

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THE EVALUATION OF HIGH MOLECULAR WEIGHT METHCRYLATE AS A TREATMENT OPTION FOR SHIRNKAGE CRACKS

I. Introduction

The purpose of this research was to study and evaluate high molecular weight methacrylate (HMWM) as a treatment option for shrinkage cracks in concrete airfield pavement. Two main criteria were examined while investigating HMWM: how well it penetrates cracks in concrete, and how well it bonds to concrete and resists water intrusion. After conducting a literature review to determine how well HMWM has performed in these areas, laboratory experiments were conducted to see if the sealant could penetrate a crack 24 inches deep, bond to the concrete, and resist water intrusion.

Background

Concrete has been utilized for decades and is an integral piece of any civilization's infrastructure. However, due to the rigid nature of concrete, cracks always form. When cracks form and grow, they provide openings for water to infiltrate and get inside the concrete slab. Once inside, the water can freeze and expand, thus creating a larger gap. If this process happens repeatedly, it will cause the crack to become large enough to warrant removal of the slab. Another problem that can occur when water infiltrates into a crack is corrosion of the rebar, which leads to larger cracks and a weaker slab. To avoid these issues, cracks need to be treated, which takes money and time.

One treatment option for cracks is to apply sealers either over or in the crack. The sealers do not prevent the cracks from forming but from becoming wider. Sealers help to avoid issues by penetrating into the cracks and forming a tight bond with the concrete. This seals the cracks to prevent moisture intrusion and, in some cases, restore the flexural strength.

Methyl methacrylate (MMA), a methacrylate-based sealant, is an option that has been evaluated in many areas to include crack repair on bridge decks. It cures relatively quickly and possesses the ability to be used at lower temperatures where other sealants, such as epoxy, cannot (Lu and Barter, 1998). Unfortunately, studies have found that it either dripped out of the bottom of cracks or evaporated before it could cure (Rodler, 1988).

HMWM has also been evaluated as an option for crack repair. HMWM is similar to MMA; however, it has a higher viscosity (around 12 to 15 centipoise compared to 1 centipoise for methyl methacrylate (NOAA n.d.)) because of its higher molecular weight and a higher flash point (Rodler, 1988). HMWM consists of an assembly of several units of methyl methacrylate that have been covalently bonded together through chemical reaction, thus leading to a higher molecular weight molecule. Both MMA and HMWM contain carbon-to-carbon double bonds which allow these monomers to be converted into a very high molecular weight linear polymer, usually through the process of free radical initiated polymerization. HMWM is actually a system comprised of one or more types of methacrylate monomers (also called the “neat resin”), an initiator that starts the chemical reaction, and a promoter that ensures the full reaction takes place. These components are kept separated until the materials are ready to be used. They are then mixed together,

inducing an oxidation/reduction reaction to occur and producing an intermediate free radical species. This causes the monomers to react in a chain reaction to produce a high molecular weight linear polymer (Damico, 1990).

HMWM began as a material for polymer concrete for repairing Portland cement concrete, but it soon was used for bridge deck sealers. Rodler et al. (1989) showed that HMWM can prove to be a viable option for repairing small cracks in highway pavement. They ran experiments using concrete beams and small slabs where they broke the beams and slabs, applied HMWM over the crack, and examined how deep the HMWM penetrated into the crack. They found that the HMWM penetrated about 90-95% of the crack depth in a six-inch-deep beam. They also found that contaminants, such as silt or oil, which can partially fill cracks prevent the HMWM from fully penetrating the crack. Since then, studies have been done evaluating the use of HMWM on bridge decks which, again, have shown promising results on HMWM effectiveness.

Problem Statement

While HMWM has produced promising results on bridge decks, no research has been done for airfield pavements. Airfield pavements introduce a new variable because of the depth of the pavements. Airfield pavements are sometimes over 24 inches in depth while most major highways are usually about half of that. Most of the testing has been done on concrete slabs averaging only 6 inches. Greater depths can pose a problem because it creates a longer path for the HMWM to travel. During the time the HMWM is seeping into the crack, it could cure before it reaches the bottom of the concrete, which will result in a partially filled crack.

The Air Force's primary mission revolves around the airfield and its ability to launch aircraft. The vast majority of the airfields in the Air Force are made out of concrete so crack repair is a constant cost to bases worldwide. Money is a major factor because the base has to request money for a project to fix the airfield; this takes away money that could be used to fix another portion of the base. Time is crucial because the repair procedure causes parts of the airfield to shut down which is severely detrimental to the base since necessary training and missions cannot be accomplished.

Currently, the Unified Facilities Guidance and Standards only calls for epoxy to be used as a sealant (USACE, 2017) to treat the cracks. Epoxy is a very strong material and commonly used to repair roadways due to its strength and bonding ability. However, epoxy usually has to be pressure injected to work. There are epoxies that have a lower viscosity (around 100 centipoise) for gravity filling, but they generally require more time due to their higher viscosity. This makes it difficult to penetrate fine cracks, such as shrinkage cracks, as well as deep cracks, that form in concrete. This problem has led the Air Force Civil Engineer Center (AFCEC) to investigate the possibility of using a methacrylate-based sealant as an alternate method to repairing shrinkage cracks. Shrinkage cracks are narrow in width (usually less than 2.0 mm ("Plastic Shrinkage Cracks" n.d.)), which make them harder to repair because the sealers must be gravity fed as opposed to pressure injected (Rodler, 1988). HMWM is more likely to penetrate very fine cracks because of its low viscosity. These issues led to the need for a study to determine if HMWM can reach the bottom of the crack and if not, what is needed to be done to ensure that it does.

Research Questions

The primary purpose of this research is to answer the question: can a methacrylate-based sealant, specifically HMWM, be used to treat shrinkage cracks in airfield pavement in lieu of epoxy. HMWM has benefits over epoxy such as lower costs and better workability that enables it to be sprayed or rolled. Through laboratory experiments, this research addressed the above question by answering the following investigative questions.

- Can HMWM penetrate and reach the bottom of very fine cracks that are 24 inches deep? The typical airfield pavement is over 16 inches with some of the thicker pavement reaching over 24 inches. While a sealant can still keep out water intrusion by penetrating the first few inches, it would be ideal for the sealant to penetrate the entire length of the crack so issues such as capillary rise under the pavement or infiltration from other openings do not occur.
- What is the viscosity of various HMWM products at different temperatures? It will be important to record the viscosity of the HMWM at this point because not all commercial HMWMs have the same viscosity. Once the viscosity is recorded, it can be used as a benchmark for future use either in the field or a lab.
- What other physical characteristics are recommended for the HMWM? While viscosity is the most important, other characteristics such as elongation, tensile strength, and durability are also important.

Methodology

The research used laboratory tests to examine how well HMWM works for sealing cracks. Tests were performed on three HMWMs (TK-2415, Kwik Bond KPB 103, and Castek T-70) and one epoxy (TK-2110) to determine the viscosities of both the neat monomer and the sealants after mixing the components together. During these experiments, one of the variables adjusted was the ratio of the promoter and initiator. The final test on the sealants was a gel time test to determine their respective working times.

Concrete specimens were broken to create 24-inch deep cracks. For each specimen, the two halves were joined together to create cracks with widths of 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1.0 mm. The concrete was Type IA and a mixture design from the local ready-mix plant was used. The sealants were applied by pouring the liquid resin into the crack. The excess resin was forced into the crack with squeegees. Once the sealants had time to set, water with dye was poured and allowed to sit atop the specimens to determine if the water penetrates the cracks. The specimens were then separated again at the initial crack to examine how deep the sealants penetrated. The goal of the research was to determine if the sealant would penetrate the full depth of the crack, form a strong bond with the concrete, and resist water intrusion.

Limitations/Assumptions

The laboratory where the experiments took place is at a distant location so only one concrete placement took place. Due to the single placement, only 32 beams were used which may not be the ideal number to gather enough data. There was not enough time or

a location available to perform any tests on actual airfield pavement so only laboratory procedures were conducted. The cracks in the concrete were not in a confined location like they would be in actual pavement, so the HMWM was not contained in the specimens despite efforts to do so. The effort to contain the HMWM led to taping the crack on the sides of the specimen, which made it impossible to determine crack width along the entire depth of the specimen. To help minimize the effects of these limitations, the following assumptions were made.

- The results found in the laboratory experiments can be duplicated in the field.
- In the laboratory experiments, a concrete beam with a depth of 24 inches will produce results that can be translated to depths both larger and smaller than 24 inches.
- Cracks that are created in the laboratory experiments are similar to cracks found in the field.
- The crack widths are the same throughout the depth of the specimen.
- In the field, the cracks will be in a confined location such that the HMWM cannot escape either out the sides or the bottom of the crack.

Preview

An in-depth literature review is presented in Chapter II and a more in-depth methodology is given in Chapter III. The results from the laboratory experiments along with the analysis of those results are shown in Chapter IV. Chapter V provides the conclusions and a summary of the results from the research.

II. Literature Review

This chapter reviews the relevant research done on high molecular weight methacrylate (HMWM), starting with methyl methacrylate (MMA). MMA was used before HMWM but both contain the methacrylate monomer and share similar characteristics. MMA has been used in many ways but has not performed well as a crack repair option. In some areas of crack repair, HMWM has shown the ability to perform as well as, if not better, then other popular sealants such as epoxy. It has been used and tested on numerous bridge decks throughout the United States with success.

Methyl Methacrylate

Methyl methacrylate has been widely known since the 1960s after researchers from the Brookhaven National Laboratory in the United States performed extensive research using it and other monomers to produce polymer-impregnated concrete (Fowler, 1999). Since then, it has been used in three primary ways: for reflective paint marking materials, as the monomer to produce prepackaged polymer concrete for repairing pavements and other concrete structures, and for overlays to protect bridge decks and pavements.

Methyl methacrylate has been used for reflective paint marking materials due to its low volatile organic compounds content, moderate cost and durability, and the fact that it can be reapplied over old thermoplastic markings (Jiang, 2008). Methyl methacrylate was found to be highly durable and can be sprayed or extruded, which is beneficial over epoxy because epoxy must be injected (Andrady, 1997). Additionally, methyl

methacrylate was found to be beneficial because it could be used to produce polymer concrete that could be placed in a wide range of temperatures, and was resistant to oils, anti-freeze, and other chemicals commonly found on roadways (Gates, Hawkins, and Rose, 2003).

Lu and Barter (1998) conducted a study on traffic marking materials in Alaska and other northwest states and found, that methyl methacrylate demonstrated the best suitability for extremely cold environments. They compared tapes, thermoplastics, methyl methacrylate, and traffic paints; and their results were based on information surveys, field surveys, field experiments, and expert opinion surveys. They even had field engineers inform them that methyl methacrylate can be applied at temperatures as low as -18ºC (Lu and Barter, 1998).

Kim and Lee (2009) examined an alternate way to waterproof bridge decks using methyl methacrylate. The methyl methacrylate acts as a waterproofing barrier underneath the asphalt pavement but above the bridge deck. This barrier helps protect the bridge deck from water and chlorine ions that ruin the deck. They performed laboratory tests to compare the flexural strength and failure strain in a methyl methacrylate layer with a Guss asphalt mixture which is commonly used as a waterproofing layer. The methyl methacrylate outperformed the Guss asphalt mixture in every test. They also conducted a field study on an existing bridge, which had suffered from severe cracking and stripping, by placing methyl methacrylate mortar over the deteriorated cement. Three months, and again at twenty months, after the placement, observations showed the pavement surfaces were dry three days after snowfall. They

concluded that methyl methacrylate could be a good option for waterproofing bridge decks (Kim and Lee, 2009).

Dry (1994) examined the use of hollow porous fibers filled with a chemical to repair cracks or fill voids in concrete. These chemicals would release from the fibers either from human intervention, known as active mode, or without human intervention, known as passive mode. One of the chemicals examined was methyl methacrylate, which was released in the active mode. Once the methyl methacrylate was released, heat would be induced to the monomer such that it would polymerize and harden in the open spaces. Dry (1994) found that the release of methyl methacrylate reduced the permeability of the concrete without sacrificing strength. Dry (1994) later expanded on the previous work by examining an alternate form to polymerize the methyl methacrylate. She listed other promising characteristics in that methyl methacrylate has shown the ability to resist the effects of temperatures between -20 and +160ºF; it also has the viscosity of water, thus allowing it to flow into small cracks. Similar to her previous results, she found that methyl methacrylate restores the lost strength and increases the flexibility of the concrete (Dry and McMillan, 1996).

Tittelboom et al. (2011) expanded Dry's (1994) research by manipulating certain characteristics of methyl methacrylate such as viscosity, concentration of initiator and promoter, molecular weight, curing time, and strength to optimize the concrete healing agent. One means they used to manipulate some characteristics was to add polymethyl methacrylate to the methyl methacrylate base. This addition increased both the viscosity and molecular weight. By comparing their laboratory results with known suitable commercial healing agents, which have already had investigations done on their self-

healing efficiency, they selected 35 centipoise to be the optimal viscosity. They found that methyl methacrylate without any polymethyl methacrylate had the lowest viscosity and the quickest flow time through cracks. The research suggested that this was because the methyl methacrylate was absorbed into open pores of the concrete. This occurred because the methyl methacrylate has small molecules that can enter the pores of the concrete. By introducing polymethyl methacrylate, Tittleboom et al. (2011) introduced larger molecules which could not enter the pores, thereby enabling the higher viscosity mixtures to actually flow more quickly. The viscosity is a function of the molecular weight, and they found that the lower the concentration of initiator and activator, the higher the molecular weight (Tittelboom et al., 2011). The initiator and activator create crosslink points on the methyl methacrylate monomer chain, and the molecular weight is the distance between these two points. So when there are fewer molecules to react with the methyl methacrylate monomer, the monomer has longer distances between crosslink points and a higher molecular weight. A higher molecular weight also leads to a higher viscosity (Klosterman, 2018). Their laboratory testing yielded results showing that the methyl methacrylate penetrated deeply into the crack and made the cracks as watertight as uncracked samples.

High Molecular Weight Methacrylate

While methyl methacrylate offers the many benefits previously listed, it does not work well for repairing cracks because it is either absorbed by the pores in the concrete or evaporates too quickly. In the early 1970s, the Rohm and Haas Company developed HMWM. HMWM has a higher molecular weight, and a higher viscosity than methyl

methacrylate, which enables the material to flow through cracks without being absorbed or evaporating. Furthermore, HMWM has less odor and a higher flash point than methyl methacrylate due to its higher molecular weight (Mangum et al., 1986).

HMWM began as a material for polymer concrete for repairing Portland cement concrete, but it soon was being used for sealing bridge decks. The California Department of Transportation (Caltrans) was the first to use HMWM for sealing cracks in bridge decks in 1981, when it was used on the lift span portion of the Rio Vista Bridge near Sacramento, California (Liang, Gallaher, and Xi, 2014). The concrete was very porous since it was made with porous light weight aggregate concrete; as a result, the deck would absorb a large amount of water during rainy weather. This meant that the counterweights had to be adjusted so the bridge could lift properly and then readjusted later after drying (Mangum et al., 1986). After HMWM was applied to the surface in 1981, the counterweights had not been adjusted as of 2012 (Fowler, 2012). Caltrans eventually developed a specification for the application of HMWM due to the success of the treatment.

At the time of the application to the Rio Vista Bridge, Mangum et al. (1986) was performing research for Rohm and Haas to determine how well the new HMWM performed as the monomer for polymer concrete with its reduced odor, greater viscosity, and less evaporation. With the success of the Rio Vista Bridge, the focus of the research turned to using HMWM for crack repair. Eventually, the researchers worked with the Center for Transportation Research at the University of Texas to repair cracks in bridge decks using HMWM. The results were very promising and led to a number of bridges in Texas being treated with HMWM to seal cracks. The researchers tested HMWM in the

laboratory and in the field. Their lab testing involved making 30cm x 14cm x 36cm concrete specimens and breaking them to create crack widths ranging from 0.2 mm to 2.0 mm. They applied the monomer system by brushing it on the slab and allowed it to cure for 24 hours. One specimen was saturated with water for 24 hours prior to monomer application to evaluate the effects of water on the monomer application. They cut the specimens perpendicular to the cracks in three locations to determine the percentage of crack length filled and re-cracked the others to determine the new location of the crack and flexural strength of the repaired crack.

Some slabs were placed outdoors in approximately 100ºF air temperature just before monomer application to determine if the higher concrete temperature would cause premature curing of the monomer system and therefore reduce penetration into the crack. They found that the monomer system almost never terminated at a single depth; instead, it developed very small air pockets, thereby making the sealant discontinuous throughout the crack. These air pockets were considered when determining the depth of the crack filled. Table 1 shows that the percent of crack depth filled was at least 60 percent for all specimens, with the majority being filled over 90 percent. The wet specimen was the one exception as it was only filled at 50 percent, thus indicating that the presence of water greatly affects the performance.

Table 3. Percentage of Crack Length Filled by Monomer Systems

(adapted from Mangum et al., 1986)

Specimen	Crack Width (mm)	Monomer System	Percent of Crack Depth Filled
1	1.5	200	95
2	1.0	200	95
3*	1.0	200	50
4	2.0	200	97
5	0.4	1300	80
6	0.2	400	90
7	0.4	1100	95
8	0.2	400	60
9**	0.7	200	80
10	0.5	1100	90
11	0.8	1300	90
12	0.3	200	90
	Average (excluding specimens 3 and 9)		88

* Wet Specimen

** Applied outside under hot conditions

After re-cracking the specimens, Mangum et al. (1986) found that the new cracks coincided with the initial crack along less than half its length; this showed that the monomer system treatment has a high chance of restoring the original strength of the concrete. The re-cracking strength of the wetted specimen was much lower than the other specimens, which indicated a loss of bond between the concrete and the monomer system. Table 2 shows the positions of the new cracks, and Figure 1 defines the crack locations.

Table 4. Location of New Cracks

(adapted from Mangum et al., 1986)

Specimen	Crack Width (mm)	Recracking Stress Initial Cracking Stress	Position of Recracking Crack in Relation to Original Crack
1	1.5	0.8	Parallel
2	1.0	1.16	Partially Inside
3	1.0	0.41	Partially Inside
4	2.0	0.83	Totally Inside
5	0.4	0.78	Parallel
6	0.2	0.95	Parallel
7	0.4	1.34	Parallel
8	0.2	1.07	Partially Inside
9	0.7	0.16	Mostly parallel
10	0.5	0.96	Mostly inside
11	0.8	1.03	Totally Inside
12	0.3	-	-
13	1.3	0.97	Totally Inside

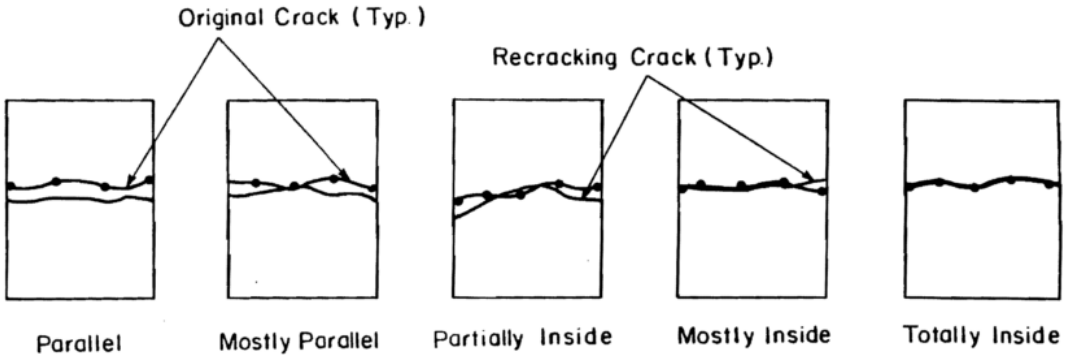

Figure 1. Location of New Cracks (Mangum et al., 1986)

Magnum et al. (1986) performed many field tests in Texas, primarily on bridge decks and found the HMWM treatments were generally successful in sealing cracks unless the cracks contained silt or debris. The monomer system cured in one to two hours and also needed a light application of sand broadcast on the surface to absorb excess monomer and to increase the friction until the polymer film wore off. The results of all the tests showed HMWM possesses the capability to fill cracks as small as 0.2 mm up to 95 percent or more. Wet concrete needs at least 24 hours of drying time before the HMWM can be applied. HMWM formed a bond as strong if not stronger than concrete as many specimens formed cracks outside the repair zone.

Rodler (1988) and Rodler et al. (1989) performed a series of tests to evaluate the structural integrity of repaired cracks along with the capability of the monomer systems to fill the cracks. They used two different types of specimens: a 10cm x 15.2cm x 30.5cm beam, and a 15.2cm x 15.2cm x 91.4cm slab. The beams were used to determine the change in stiffness at service loads between the cracked unrepaired condition and the cracked repaired condition. The slabs were used to compare the moduli of rupture before cracking and after repair. They used three different types of HMWM monomer systems and filled each crack until penetration into the cracks had stopped. Additionally, small 2.5-cm diameter mortar cylinders were made, broken, and repaired with the monomer system that was cured. The repaired cracks had widths of 0.4 mm and 1.0 mm. The specimens were tested in tension, and it was found that the monomer system with the lowest modulus of rupture showed the greatest increase in ultimate strain with increasing crack width. The three different HMWM monomers systems had different moduli of rupture. With the slabs, they found that the more rigid monomer system filled the cracks

very well, even cracks as small as 0.1 mm. As the crack width increased, the re-cracking stress/original stress ratio decreased, which represented a decrease in re-cracking strength. The less stiff systems showed the opposite, with lower stress ratios for the small cracks. Rodler et al. (1989) concluded that the monomer system with the higher modulus of rupture is more suited for repair of the smaller cracks.

Rodler et al. (1989) repeated the slab tests while applying the HMWM system under sunny and hot conditions. The heat and ultraviolent radiation accelerated the curing of the monomer system, which reduced the time the system had to penetrate the crack before it hardened. The system with the lowest modulus of rupture was found to have only a five percent reduction in amount of crack depth filled, while the other two had a 10-15 percent reduction. They also tested the slabs after they were saturated and allowed to dry for differing periods of time before the HMWM system was applied. The results indicated that moisture on the concrete affects the bond between the concrete and the monomer. Three days was found to be a sufficient drying time to develop 95 percent of the expected re-cracking stress/cracking stress ratio. However, only two days of drying were needed to provide 95 percent of the expected filling of cracks if only crack sealing is desired.

With the beams, Rodler et al. (1989) cracked and then repaired them with the HMWM systems. They then reloaded the beams and recorded center-point deflections. The results showed that the most flexible polymer had the highest deflection while the most rigid polymer had the lowest deflection. It was concluded that for the repair of flexural members, a more flexible polymer should be used. Rodler et al. (1989) reached this conclusion because the deflection of the beam across the repaired crack causes most

of the force to be accommodated by the polymer due to the higher modulus of rupture of the concrete.

Overall, they stated that important properties affecting the repair of cracked concrete with HMWM include modulus of rupture, effect of heat and sunlight while curing, and the effect of moisture in the crack (Rodler et al., 1989; Rodler, 1988). Consideration should be given to the modulus of rupture of the polymer and the strains it will undergo when choosing a system. Systems using benzoyl peroxide as the initiator were more sensitive to heat and sunlight while curing than systems using cumene hydroperoxide. Lastly, moisture had a negative effect on the performance of the system, no matter how much was present.

Since the time when the previous experiments were performed until today, HMWM has been primarily used to seal bridge deck surfaces and cracks. There have been many studies done on how well HMWM performs in Virginia, Iowa, Kansas, California, North Dakota, Florida, and Colorado. In the late 1980s for instance, the Virginia Research Council along with the Virginia Department of Transportation applied HMWM resins to two bridge decks. Since both transverse and longitudinal cracks were observed on the bridges, they decided to try HMWM because it had an anticipated lower cost than epoxy. In the 1980s, epoxy still had to be injected which led to much higher labor costs and longer time periods for work while HMWM could be applied using easier methods. The HMWM was sprayed onto the deck between 1 a.m. and 11 a.m. at deck surface temperatures between 55ºF and 70ºF. Temperature was taken into consideration because the temperature in the concrete would increase as the ambient temperature increased, thereby causing the concrete to expand and reduce crack widths. Examinations were then

done on 10.2-cm-long cores taken from the bridges by cutting and examining them under the microscope. Figures 2 and 3 give results of these examinations and provide a number of conclusions. Cracks tended to be less than 0.2 mm below the surface, and many cracks were much wider at the surface than below. Additionally, transverse cracks were usually wider than longitudinal cracks. Finally, the HMWM did not fill the cracks very well at depths greater than 12.7 mm from the surface.

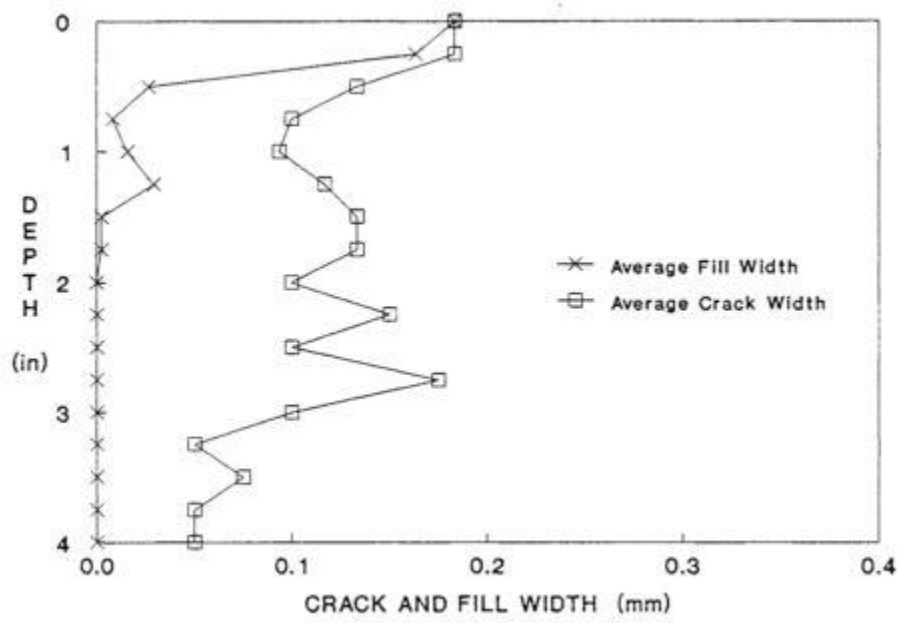

Figure 2. Crack and Fill Width vs Depth for Transverse Cracks (Sprinkel, 1991)

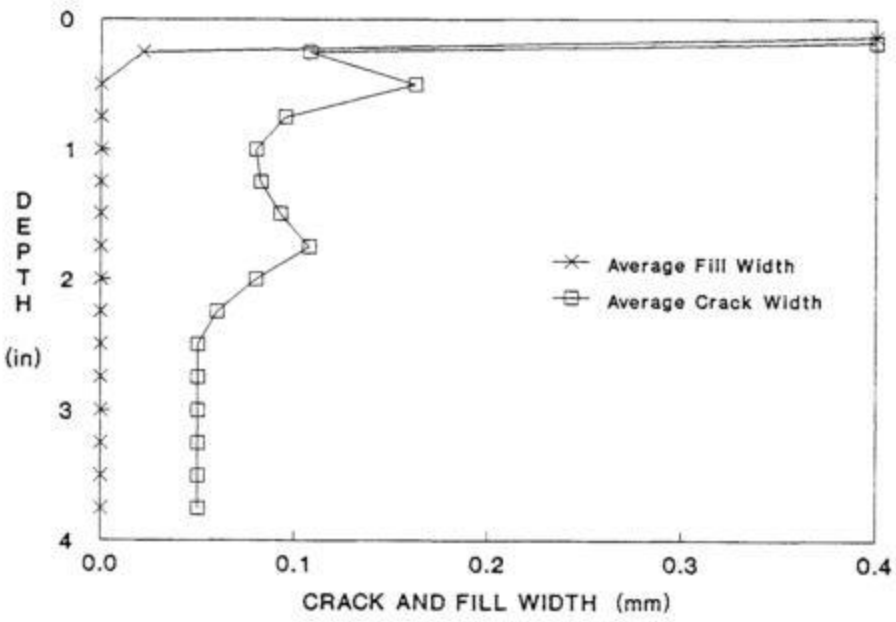

Figure 3. Crack and Fill Width vs Depth for Longitudinal Cracks (Sprinkel, 1991)

Flexural tests found that the HMWM did not restore the flexural strength of the concrete. The average modulus of rupture was 758 kPa compared to 6825 kPa for the uncracked concrete with all re-cracking occurring at the original cracks and not in other parts of the concrete. It was noted that 60 percent of the failure locations in the upper 5 cm and 100 percent in the lower 5 cm contained dirt and other debris when the monomer system was applied. This likely affected the results of both the penetration and the flexural strength (Sprinkel, 1991). Tensile tests and skid tests were also conducted by the Virginia Department of Transportation. The HMWM restored the tensile strength of the concrete across the crack and provided acceptable skid resistance, along with a light application of sand, to the surface of the pavement.

The HMWM was applied to another bridge during this time period with tests conducted for waterproofing ability. The results indicated that the HMWM performed as

well as the epoxy sand overlay which is a commonly used waterproofing material. A number of conclusions were drawn from the aforementioned experiments (Sprinkel 1991). First, cracks that are wider than 0.2 mm are better suited for the HMWM monomer treatment. Second, the HMWM did not restore load transfer across the cracks because it did not completely fill the cracks due to the presence of dust and other debris in the cracks. Because of the debris, it is unlikely that the HMWM was able to bond the concrete together. Third, the HMWM treatment reduced the permeability of the concrete to the chloride ion. Finally, the HMWM along with an application of sand can provide acceptable skid numbers.

At about the same time the studies were being done in Virginia, the Iowa Department of Transportation (DOT) was evaluating HMWM as well (Marks, 1988). The Iowa DOT had a project where they used a spray bar to apply HMWM over a bridge deck with very fine, transverse cracks that traveled the full depth of the deck. During periods of rain, water was observed dripping from the cracks under the bridge deck. Initially, the Iowa DOT tried three conventional sealants on small areas of the bridge deck, but none of them prevented water from passing through the cracks even though the sealants penetrated into the cracks. This led them to investigate the use of HMWM since Caltrans had success with it and had developed specifications. The Iowa DOT applied the HMWM at 8:00 a.m. and found that leaks were still occurring. They attributed this to the rapid temperature rise and expansion of the concrete deck. They applied the HMWM again, using a single application in one area and a double application in another. The monomers were applied prior to 7:00 a.m. before the deck temperature had risen. Tests and observations the next morning revealed slight leakage through the area with a single

application and no leakage in the area with the double application. From these results, it was determined that time of application affected performance, and the Iowa DOT decided to use HMWM to seal the rest of the bridge deck with a single application.

After the HMWM was applied to the bridge deck, experiments were run on six cores to evaluate the performance of the HMWM in the areas of penetration and skid resistance (Marks, 1988). The cores revealed the HMWM had penetrated at least two inches deep at all core locations and provided acceptable skid resistance. Further observations of the bridge deck after treatment, revealed leakage even after a second application was applied. Additionally, the friction levels of the bridge deck decreased to the pretreated levels, which indicated that the resistance wore off over time.

Sprinkel and DeMars (1995) performed further laboratory experiments in Virginia to examine three epoxies, one HMWM, and one polyurethane. They measured flexural strength and freeze-thaw durability of repaired beams, along with the gel times and penetration abilities of the sealers. They also evaluated the sealers with respect to the effects of temperature and crack width on the quality of repair, cost, ease of application, safety, appearance, and odor. They used beams measuring 7.6cm x 10.2cm x 27.9cm and recorded the ultimate strengths by cracking them. The broken pieces were held together using wire spacers with diameters of 0.2, 0.5, 0.8, and 1 mm. The polymer was applied, usually needing to be applied several times to completely fill the crack due to leakage and long penetration times. After two weeks, the beams were tested again for the ultimate strengths and to see where cracks appeared. It was noted that the vast majority of the failure appeared in the concrete, as shown in Figure 4.

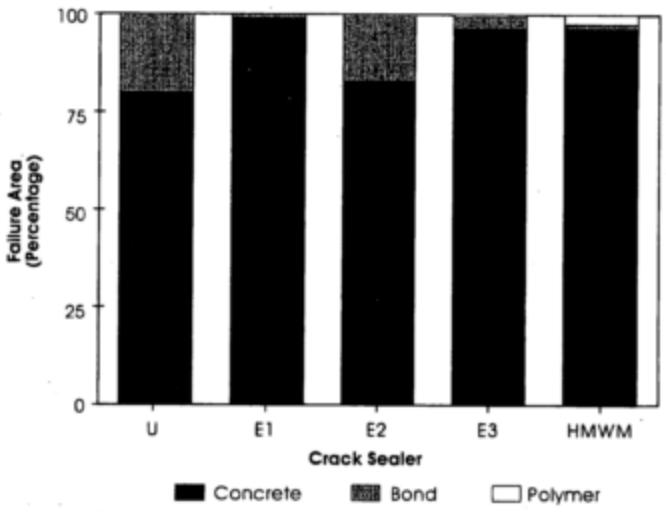

Figure 4. Failure Mode of New Crack (Sprinkel and Demars, 1995)

The freeze-thaw test conducted by Sprinkel and Demars (1995) determined the durability of the polymer repairs when subject to freeze-thaw conditions. More beams, measuring 7.6cm x 10.2cm x 40.6cm, were cracked and repaired. The repaired beams went through 480 cycles of freezing and thawing because they performed so well at the ASTM C666 recommended 300 cycles. The repaired beams were tested using flexural loading and the strengths were recorded. Although the strengths were less, the majority of the failures occurred in the concrete. To test the gel times of the materials, they measured the time it took for the materials to reach a consistency of Jell-O and be unable to flow along the side of a tipped cup. They did this at different temperatures and found that the gel time decreased as the temperature increased and vice versa. The polyurethane gelled the fastest, then an epoxy and HMWM, with the other two epoxies taking considerably longer times, as shown in Figure 5.

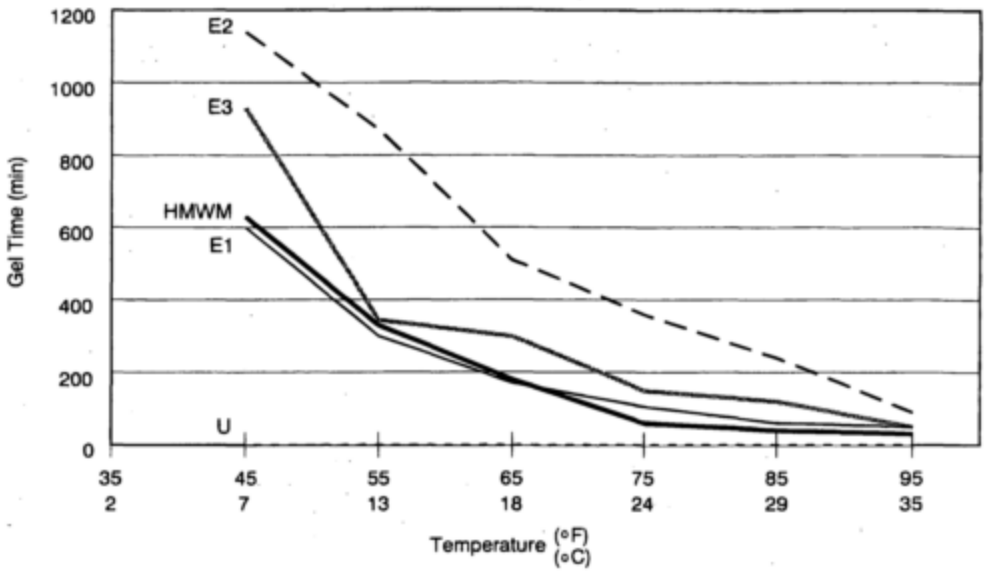

Figure 5. Gel Time vs Temperature (Sprinkel and Demars, 1995)

To examine the polymer's ability to penetrate, Sprinkel and Demars (1995) poured the polymer over different gradations of dry filter sand, let the material cure, brushed off the excess sand that did not bond, and then weighed the sand. Using the difference in weights, they determined which material penetrated the best. As shown in Figure 6, HMWM penetrated 100 percent of all samples and at all temperatures, two epoxies penetrated the second and third best, the polyurethane was the worst, and the last epoxy provided inconsistent results.

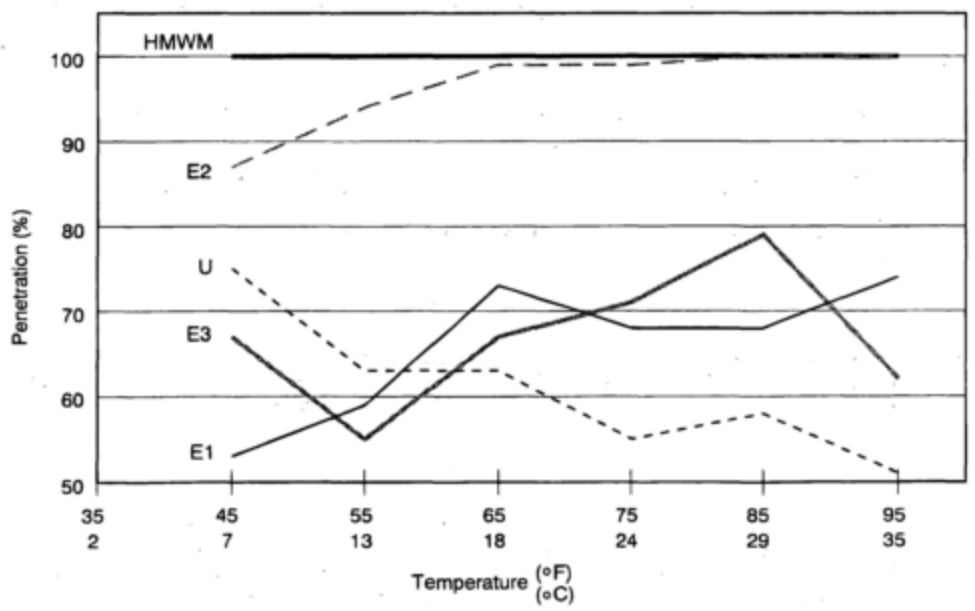

Figure 6. Percent Penetration vs Temperature (Sprinkel and Demars 1995)

Meggers (1998), along with the Kansas DOT, conducted both field and laboratory studies to determine if using HMWM and epoxy is feasible on older bridges. They applied two different HMWMs and one epoxy sealer to eight bridges throughout Kansas and conducted field studies by removing cores from the bridges. They removed the cores a few months after sealant application, then again three years after application. The chloride concentration was taken before and after the sealers were applied to the bridge deck along with the penetration of the sealers. Due to variability in both the chloride concentration and penetration results, they conducted laboratory studies using concrete beams measuring 75mm x 100mm x 400mm. The laboratory tests included wet/dry, freeze/thaw, and salt ponding to see how well the sealers would withstand the tests.

From the field studies, Meggers (1998) found inconclusive results in the sealers' abilities to resist chloride intrusion. The average chloride concentration values were inconsistent and indicated very little difference as to the effectiveness of the sealers.

They concluded that this could indicate the sealers were trapping the chlorides in the system and could actually make the system worse. For their penetration results, they found that full penetration generally happened above a crack depth of 30 mm while partial penetration generally happened below 60 mm. Furthermore, there was a tendency for full penetration of the sealants in cracks less than 0.5 mm wide. The authors predicted this due to the fact that debris has a more difficult time entering narrow cracks as opposed to wider cracks. Between the HMWMs and epoxy, they found that one of the HMWMs had the highest percent penetration average as shown in Table 3. This indicates that HMWM has the ability to penetrate the cracks better than epoxy.

Table 5. Average Crack Width Penetration and Percent Penetration (Meggers 1998)

		Average Crack Width (mm)	Average Penetration (mm)	Average Percent Penetration (crack area)
EPOXY				
Bridge A		0.58	33	53
Bridge B		0.48	51	68
Bridge C		0.6	32	38
Bridge D		0.58	40	38
Bridge E		0.1	37	83
Bridge F		0.54	21	30
Bridge G		0.16	21	48
Bridge H		0.18	40	78
	AVE	**0.4**	**34**	**55**
HMWM A				
Bridge A		0.4	66	70
Bridge B		0.43	45	68
Bridge C		0.27	26	34
Bridge D		0.81	39	61
Bridge E		0.19	22	38
Bridge F		0.19	33	51
Bridge G		0.18	35	70
Bridge H		0.05	52	100
	AVE	**0.32**	**40**	**62**
HMWM B				
Bridge A		0.37	44	66
Bridge B		0.6	42	50
Bridge C		0.74	22	32
Bridge D		0.47	20	51
Bridge E		0.29	27	66
Bridge F		0.4	30	61
Bridge G		0.14	31	84
Bridge H		0.05	33	70
	AVE	**0.39**	**32**	**60**

Meggers (1998) found much better consistency with the laboratory tests. The Kansas DOT added another HMWM for these experiments and noted that there is a noticeable difference in performance among the four sealers for resisting chloride intrusion. Performance seemed to be a function of the material properties such as viscosity, flexibility, and tensile strength rather than depth of crack penetration. Each sealer penetrated the crack to the depth of the reinforcing steel at 50 mm. However, after undergoing freeze/thaw and wet/dry testing, two of the HMWMs provided protection for 8 and 9 years, which was less than desired. The epoxy and one of the HMWM performed the best in the freeze/thaw and wet/dry cycles, showing the capability to last 15 and 11 years, respectively. The evidence suggested this to be the result of the high tensile strength and elongation of the polymers. The best performing HMWM had the highest tensile strength of the HMWMs while the other HMWMs had low tensile strengths. The results indicated that a relatively low viscosity of 500 centipoise or less, high tensile strength of at least 8 MPa, and flexible material that can elongate 10 percent or more can protect a bridge deck.

In 2006, students at the California Polytechnic State University did an in-depth study on crack sealing for concrete bridge decks focused primarily on HMWM (Rahim, Jansen, and Abo-Shadi, 2006). They used a literature review on HMWM and, a nationwide survey investigating the effectiveness of HMWM as a sealer to develop guidelines for the use of HMWM. In their review of the literature, they found a wide range of application temperatures but recommended a range of 7ºC (45ºF) to 29ºC (85ºF). They recommended that HMWM be applied 3 to 6 months after construction for new decks to ensure that the chloride concentration does not reach the corrosion threshold. This also

ensures less debris and other materials in the cracks. For older bridges, extra care should be taken to ensure the cleanliness of the deck surface and cracks. Even in areas not subjected to deicing chemicals/chloride-laden environments, HMWM can be used to effectively restore the structural bond and flexural strength of the concrete but only if the cracks are free of contaminants.

Rahim, Jansen, and Abo-Shadi (2006) sent a survey to every state and received responses from 41 states. From these responses, they found that 17 states use HMWM, 21 use epoxy, 3 use polyesters, and 15 use other sealants. Some of the states reported using more than one sealant; however, it was not identified how many used it as the only sealant. For the states using HMWM, 10 states reported using it solely as a crack sealer, 1 state uses it solely as a surface sealer, and 6 states use it as a combination. Finally, they found that 12 of the states using HMWM stated they apply it to cracks that are narrower than 1.6mm, 6 states apply it to cracks ranging from 1.6mm to 3.2mm, and 1 state uses it on cracks visible to an inspector.

Vargas (2012) studied the deterioration of concrete bridge decks, to include examining sealants and their ability to repair the bridge decks. He examined the sealants by evaluating state surveys and conducted both field and laboratory studies measuring penetration depth, bond strength plus elongation with factors of temperature, type of sealant, and debris. The surveys showed that of the 40 states that responded, 60% indicated they did not have a crack sealing program. Of the states that do have a program, 24% or 16 states, use epoxies and methacrylates. Only 4 of the 16 states reported using HMWM sealers.

For the laboratory testing, Vargas (2012) tested nine concrete specimens measuring 45cm x 122cm x 14cm. Cracks were induced by placing blades into the concrete which created different widths and lengths, then the cracks were treated with four different sealants (methyl methacrylate, epoxy, HMWM, and polyurethane). For the field studies, the sealants were placed on a bridge and cores from the bridge were examined. It was found that the repaired beams had similar strength to the uncracked beams, and all sealants had acceptable penetration. Overall, it was found that HMWM performed the best for cracks less than 50mm wide and the epoxy performed the best for cracks greater than 50 mm wide.

Johnson, Schultz, and French (2013) studied crack repair and concrete deck performance, which included a literature review and survey. The literature review covered studies that are both current and significant to the field of deck and crack sealing. The survey was used to determine current and common practices for the use and application of the sealers throughout the United States. Johnson et al. (2013) used the acquired information to recommend the best materials and practices for use in Minnesota and throughout the Midwest. Their literature review focused on four areas of the crack sealants: depth of penetration, bond strength, chloride resistance, and seepage.

Depth of Penetration

Viscosity is the most important material property affecting depth of penetration, but the cleanliness of the crack plays an important role as well. The crack width and depth will affect the penetration depth as cracks that are wider and deeper tend to have a larger penetration depth, but that is not always the result. Wider cracks allow for more debris to enter, which can negatively affect the penetration depth.

When tested, all the sealers were equally effective, which may be due to the fact that the studies used a fixed or small crack depth. All of the laboratory tests were done under clean and controlled conditions so there were no contaminants in the cracks. This makes it difficult to compare lab results with field studies. Field tests indicated that HMWM and methyl methacrylates performed the best. It was assumed they achieved greater depths of penetrations due to their low viscosity. It was difficult to predict the depth of penetration for any sealant due to the varying crack sizes and contaminant build-up.

Bond Strength

Bond strength is the property of the sealant that indicates how well the structural strength is restored in the crack and how well the resin will hold up over time. Tensile strength is an indication of where the failure will occur, which can occur in three different locations: the concrete, the bond, and the sealer. If the sealant's tensile strength is similar to or greater than that of the concrete, there will be a higher chance of concrete failure. Sealers with lower tensile strengths tend to produce failures in the sealant or bond. The cleanliness of the crack and effects of freeze-thaw cycles can have significant impact on the bond strength of the sealant. Additionally, there are many other factors that can affect where the failure occurs. Dirt, contaminants, temperature, and moisture can all have an effect on the bond strength. Bond strength tended to decrease as the crack width increased. Laboratory tests showed that epoxy sealers had the best resistance to freeze-thaw effects with HMWM a close second; polyurethanes and urethane polyurea hybrids did not perform well in the testing. HMWM was the only material tested in the field.

Seepage

Seepage is an indication of how well the repaired pavement will prevent water infiltration. When analyzing the results, there were no laboratory investigations testing the amount of water seepage in the literature Johnson et al. (2013) reviewed. All the field data covered the seepage rate of the HMWM sealers. They showed that all the HMWM sealers were not able to stop the flow of water through the cracks completely.

Chloride Ingress and Corrosion

Cracks create an opening for the chloride ions to infiltrate and cause corrosion in the reinforcement. The ability of the sealers to lessen the infiltration of chloride ions is based on the performance measures mentioned above. When tested in a lab, the results were mixed concerning which sealer performed the best. The flexibility of the sealer played an important role in chloride and water infiltration. The cracks in concrete are constantly changing width due to loading and temperature changes so the flexible sealers have a greater ability to move with the concrete. The sealers that are not able to expand and contract with the concrete tend to fail, thus allowing a greater amount of chloride ions to enter into the concrete.

General Trends

Johnson et al. (2013) found other trends while conducting their literature review. They found that sealants had a wide range of lifespans, which was probably due to many variables such as location and type of experiments; sealants used in the southern half of the United States tended to last longer. Laboratory tests showed that the lifespan of HMWM can range from a short time period to around 30 years. No laboratory tests have investigated re-cracking of the concrete but a few field tests have showed that only a few,

if any, new cracks have appeared. The tack free time for sealers tended to be from three to six hours. HMWM had a typical wait time between four and five hours. Temperature has a significant effect on the gel time of the sealers. If the sealer is applied when the pavement is too hot, the sealer will cure faster and not penetrate the pavement as far. The opposite happens when the pavement is too cold since the gel time is increased and the sealer can seep out the bottom if it is placed on bridges. Most sources recommend a gel time of around one hour for HMWM resins. Field tests showed that sealers were able to penetrate new bridge decks easier than older ones. The research suggested this is due to the larger number of contaminants in the older bridges. It is best to apply the sealer at night because that is when the crack is the largest.

The type of initiator may affect the sealer's characteristics. There were no definite conclusions drawn on which initiator performed better, but cumene hydroperoxide formulations achieved a high bond strength in all the documented sealers in which it was used. Benzoyl peroxide produced a polymer that was noted to be more flexible in one study. However, since the tests had other variables, it cannot be determined if the initiator is the sole cause of these results. Little is known regarding reapplication of the sealers, thus prompting further research to be done in order to determine the effectiveness of sealer reapplication.

In 2014, students at the University of Colorado in Boulder did a study for the Colorado DOT to determine which bridge deck sealant should be used (Liang, Gallaher, and Xi, 2014). Four different materials were examined: one HMWM, two epoxies, and one silane. After the sealants were applied to a bridge deck in Denver, field tests consisted of using integrated sensors in the bridge decks to monitor internal temperature

and relative humidity, core samples to check the chloride concentrations, and a British Pendulum Tester (BPT) to measure the skid resistance. Internal temperature was measured because sealers generate heat when they cure, which can create a temperature gradient between the treated and untreated concrete. However, the gradient was small and did not affect curing. Internal relative humidity was measured to determine if moisture within the concrete increased from precipitation during an eight-month period. Since no difference was found in the moisture content, the sealers were found to be effective in blocking the moisture. HMWM and both epoxies showed an ability to effectively block the penetration of chloride ions, while silane only showed a minimum ability. It was noted that both epoxies were not as effective a year later while HMWM was still considered effective; this showed that HMWM was the more durable of the sealers. Silane performed the best in terms of skid resistance, while one of the epoxies and the HMWM were acceptable. The other epoxy did not provide adequate friction on the concrete.

In 2016, Syracuse did a report covering the economy of preventative maintenance for concrete bridges (Zhang, 2016). To accomplish this report, the University Transportation Research Center reviewed past literature that included current inspection requirements and maintenance methods. Their report briefly covered HMWM and crack sealing to draw a number of conclusions were drawn. First, decks with cracks less than 0.2 mm in width usually do not need to be filled if only subjected to moderate or slight aggressive environments. This width is similar to what can be found in ACI 224R-14 ("Control of Cracking in Concrete Structures," 2001). Second, HMWM has better performance in the

ability to penetrate narrow cracks, seal large cracks effectively, and withstand freeze-thaw. Finally, crack filling costs approximately $0.3-$1.5 per linear foot.

After reviewing the past literature, HMWM has shown the ability to be a good treatment option for sealing cracks based on the properties found in Table 4.

Table 6. HMWM Properties

Low Viscosity	the low viscosity allows for the penetration and complete filling of narrow cracks
Higher Molecular Weight	the higher molecular weight ensures the monomer is not absorbed into the pores of the concrete but adequately seals them
Acrylic Base	the acrylic base gives it a good resistance against chloride intrusion and other chemicals commonly found on roadways
Skid Resistance	the skid resistance is acceptable, but broadcasting a light sand creates a higher resistance
Strength	HMWM has a wide range of strength parameters that can meet the needs of the situation
Ease of Application	HMWM has shown the ability to be applied with a spray bar or broomed onto the concrete. This ease allows for lower costs than other sealants because the labor cost is minimized. Additionally, it does not require specialized labor to apply which some other sealants do
Durability	HMWM has shown more durability than epoxies and other sealants.

While each of the studies reviewed in this section has made great contributions towards further understanding HMWM, they have not covered the possibility of using it on airfields. Airfields, while similar to other concrete pavements, experience different stresses due to the nature of airplanes. Airplanes are heavier and can induce higher pressure on the pavements; therefore, the pavements are much thicker than roadway pavements. Additionally, airfield pavements can experience jet blast and extreme temperature along with other chemicals, such as jet fuel, not found on roadways. Due to this gap, this research, alongside the U.S. Army Corps Engineer Research and Development Center (ERDC), had the goal to evaluate how well HMWM performs in treating cracks in airfield pavement. ERDC has run laboratory experiments on different sealants, testing pot life, water resistance, thermal cycling, abrasion resistance, tensile strength, tensile extension, compressive strength, film hardness, chemical resistance, and dynamic mechanical properties. They began with 21 different materials from which the best performers were selected. After going through the 10 different tests mentioned above, an epoxy and HMWM were considered the be the best performers (Wood et al., 2018). This research will evaluate how well HMWM can penetrate a crack that is 24 inches thick and resist the intrusion of water using three of the HMWMs and the higher performing epoxy from the ERDC testing.

III. Methodology

This chapter discusses the laboratory procedures used during the research. Viscosity tests were performed on both the neat monomer and the complete mixture of the different sealants. Gel time tests were conducted next to determine the workability of the sealants. The final portion of the laboratory tests included the concrete specimens that were fabricated. These specimens were completely broken and placed back together at specific crack widths. The sealants were poured over these cracks to determine how well they could penetrate varying crack sizes. Water was then poured and allowed to pond on the surfaces of the specimens overnight. The specimens were separated again to determine how well the sealants performed.

Viscosity Tests

Sealant viscosity was measured with an Anton Paar cone and plate rheometer located at the University of Dayton and based on the instructions of Dr. Klosterman. Neat monomer was tested first. The cone and plate surfaces were cleaned using acetone while the rheometer booted up. The cone was inserted into the rheometer and set to a zero gap of 0.01 mm for testing and an open gap of 30 mm for sample insertion. A small amount of certified viscosity reference standard oil was placed on the plate, enough to permit it to seep out when the cone was in the testing position of 0.01 mm. This oil was used to confirm if the rheometer was giving correct values when measuring the viscosity using ramp and constant shear rates. The viscosity of the oil should not show any shear thinning or thickening properties because it was a Newtonian fluid; the test confirmed that the rheometer was performing properly.

The surfaces outside the cone and plate were wiped clean so only the gap between the cone and the plate contained the oil. The tests consisted of incrementing or "sweeping" the shear rate up a decade (i.e., an order of magnitude) every 40 seconds for four intervals at a constant temperature. The initial shear rate was 0.1 s^{-1} and the final shear rate was 100 s^{-1} at 160 sec. Once the test was completed, the cone was lifted to the open gap position and removed. The test apparatus was then wiped clean, along with the plate, of any material left on the surfaces and cleaned again with acetone to remove any material left on the surfaces. The cone was inserted into the rheometer again, and the zero gap was set again to ensure the point at which the cone is inserted was not moved during the removing and inserting process. The sealants were then tested.

The first neat monomer was placed onto the plate, again to a point where some of the resin would seep out from the sides of the cone. The first neat monomer tested was the TK-2415 high molecular weight methacrylate (HMWM). The excess neat monomer was wiped clean again, and the cone was set to a position of 0.01 mm. The first test on the neat monomer was a shear sweep test using the same conditions as the oil. Once these tests were completed, another set of tests was performed using the same shear rate, 1 s^{-1}, but at different temperatures for two minutes. The first tests were at 25ºC, the second at 35.5ºC, the third at 15.2ºC, and the final at 4.5ºC. Two tests were run at each temperature to ensure consistent data. Once all the tests were completed, the cone was set to the open gap position and removed to remove the neat monomer from the surface of the cone and plate. The surfaces were then wiped with acetone, and the cone was placed back into the rheometer. The zero gap was set again to ensure the correct location and then the cone

was placed back into the open gap position. The same procedures were completed for the Kwik Bond HMWM, Transpo T70-10 HMWM, and TK-2110 epoxy.

When all the tests were complete, the cone was set to the open gap position and removed. The cone and plate were wiped clean of any leftover neat monomer and then wiped clean using acetone. The cone was placed back into the rheometer, and the zero gap was set again in the same position. This set of tests was repeated once the initiator and promoter were mixed into the neat monomer, with the viscosity taken at a shear sweep and constant shear rates at different temperatures. The only difference was that no tests were conducted at 35ºC to avoid the sealants curing on the cone and plate.

Gel Time/Pot Life

Once the initial set of tests were completed, tests were completed to find the pot life of the material using small disposable containers (Figures 7 to 11). These tests were completed to find the time between the mixing of the initiator and monomer and the polymerization or hardening of the polymer. The pot life is a measure of the working time of the material. These first tests were accomplished on the TK-2415 HMWM by combining the neat monomer, initiator, and promoter using the ratios provided by the manufacturer in a disposable cup and mixing them together. For these tests, 50 mL of the neat monomer, 1.430 mL of the initiator, and 0.508 mL of the promoter were used. The measurements were taken using a graduated cylinder for the neat monomer and micro pipettes for the initiator and the promoter.

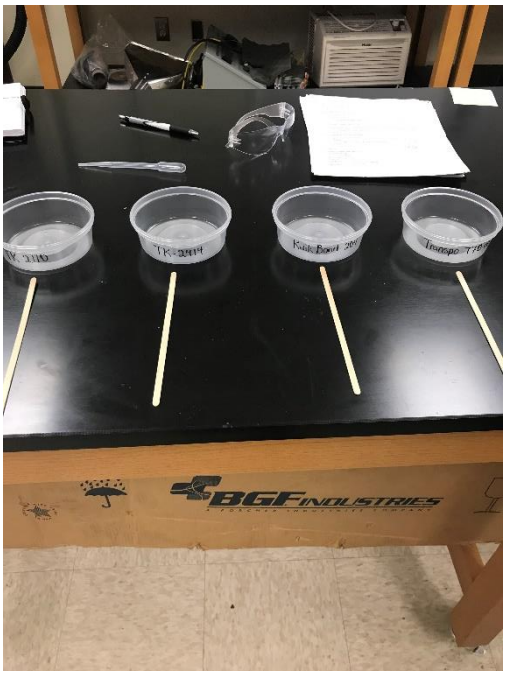

Figure 7. Gel Time Tests

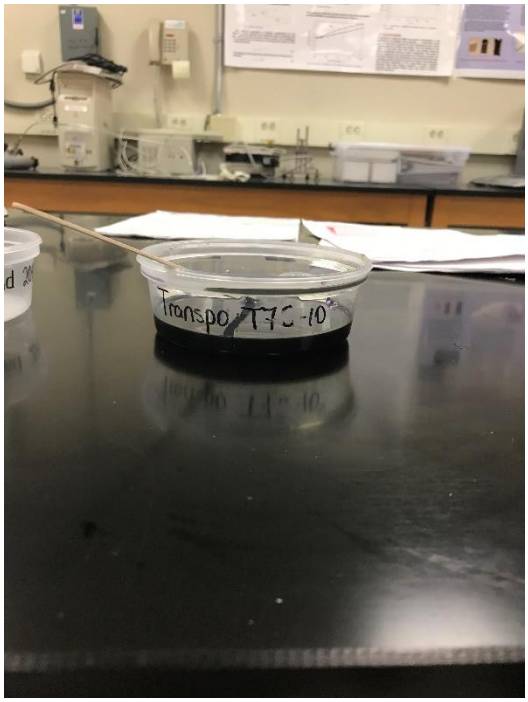

Figure 8. Transpo T70 Gel Time Test

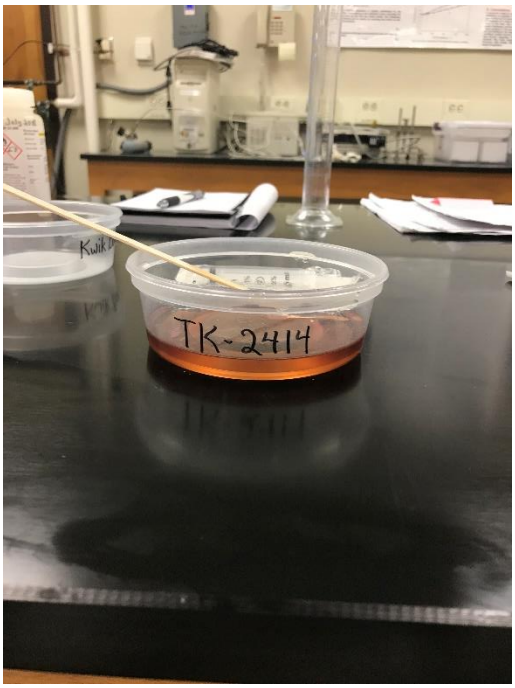

Figure 9. TK-2415 Gel Time Tests

Figure 10. Kwik Bond Gel Time Tests

Figure 11. TK-2110 Gel Time Test

The promoter was added in and stirred for a minute, and then the initiator was added in and stirred for another minute. The measured time began once the initiator was introduced to the neat monomer. The material was stirred for five seconds every five minutes until it was noticed that the consistency became similar to Jell-O and could not flow down the container when tipped. The time was recorded at this point. The same procedure was used for the other three sealants using the following mix ratios.

This test was repeated again for each sealant using the ratios shown in Table 5. The pot life was recorded with the initiator halved, the initiator doubled, the promoter halved, and the promoter doubled. For the TK-2110 epoxy, only three tests were needed: one with the manufacturer's recommended mixing ratio, one with half of the amount of part B, and one with double the amount of part B. This concluded the laboratory tests conducted on the sealants.

Table 7. Sealant Mix Ratios for Gel Time Tests

Sealant	Neat Monomer (mL)	Initiator (mL)	Promoter (mL)
Initial Tests			
HMWM			
T70	50	0.99	1.985
Kwik Bond	100	2.343	0.391
Initiator Halved			
T70	50	0.495	1.985
Kwik Bond	100	1.1715	0.391
Initiator Doubled			
T70	50	1.98	1.985
Kwik Bond	100	4.686	0.391
Promoter Halved			
T70	50	0.99	0.9925
Kwik Bond	100	2.343	0.1955
Promoter Doubled			
T70	50	0.99	3.97
Kwik Bond	100	2.343	0.782
Initial Tests			
Epoxy			
Sealant	Part A (mL)	Part B (mL)	
TK-2110	40	10	
Half Part B	40	5	
Double Part B	40	20	

Concrete Specimen Fabrication

Laboratory tests were conducted to determine the ability of the sealants to penetrate cracks in concrete slabs and resist water intrusion. The first step was to make 32 concrete test specimens. There were 16 beam specimens and 16 slab specimens, with the beam

specimens measuring 15.2cm x 15.2cm x 61cm and the slab specimens measuring 15.2cm x 61cm x 91.4cm. Wooden forms were constructed using 2x8s (Figures 12 and 13) and placed on a sheet of plywood over a large piece of plastic. The 2x8s were cut to a width of six inches to produce slabs six inches thick.

Figure 12. Beam Specimen Forms

Figure 13. Slab Specimen Forms

Two and a half cubic yards of concrete were purchased from a local ready-mix concrete plant that could meet the mixture proportions given in Appendix A. The concrete was placed into wheelbarrows, which were wheeled to the designated area with the forms. For the beams, the concrete was shoveled into the forms until the form was half full, then a sheet of Teflon was laid over the concrete, and the forms were completely filled with concrete (Figure 14). The sides of the forms were struck with a rubber mallet to improve consolidation and finished with a hand trowel. The concrete was then

shoveled into the forms until the concrete reached the top. For the slabs, the concrete was shoveled into the forms until the concrete reached the top (Figure 15). The slab specimens were then vibrated and finished with a hand trowel. The slabs had four handles with rebar placed into the concrete between the two handles on each side before finishing.

Figure 14. Finished Beam Specimen

Figure 15. Finished Slab Specimen

Concrete Specimen Cracking

After 64 days, the forms were taken apart and the specimens were broken in half. The beam specimens were pulled apart since they had the Teflon in the center, while the slab specimens were broken using a large hydraulic press. The slab specimens were placed on a wooden pallet under the press where a load was applied to the middle of the specimens until they cracked all the way through (Figure 16). Once the specimen was broken, it was removed and set to the side.

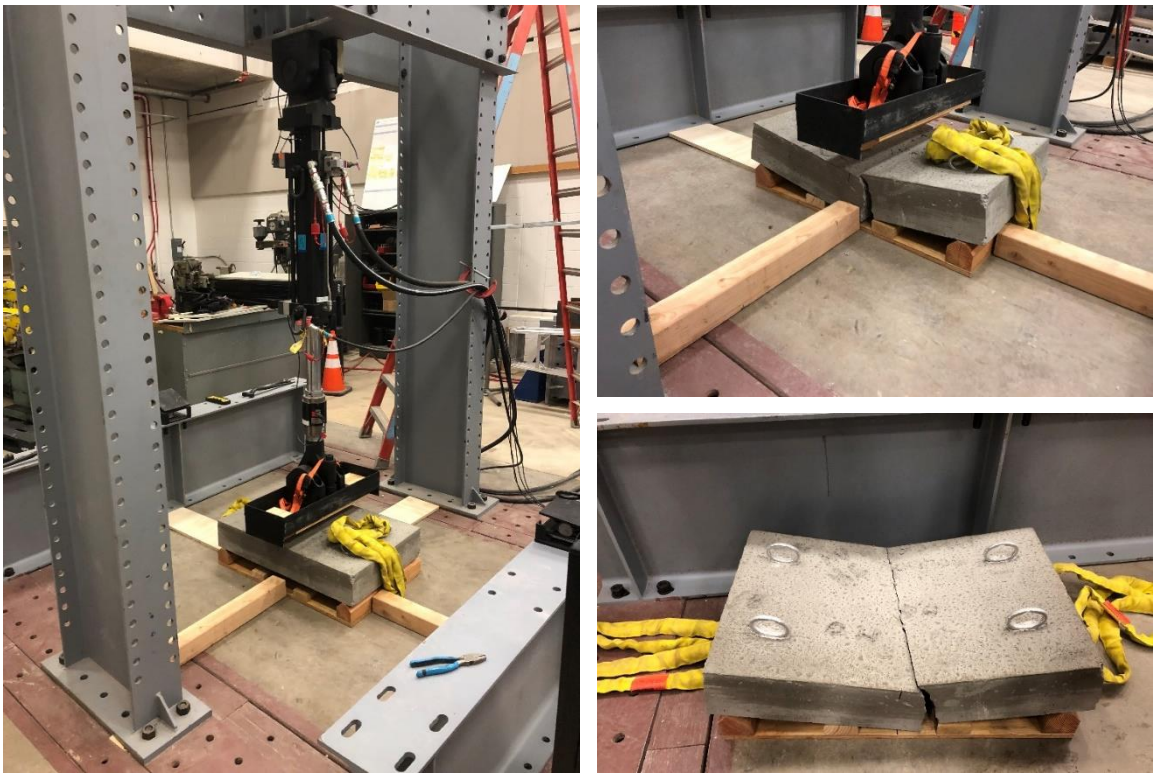

Figure 16. Breaking of Slab Specimen

Sealant Testing

The two halves of the beam specimen were placed onto a custom-built table over a piece of plastic drop cloth. The table was assembled to include adjustable edges specifically for the concrete specimens. Plexiglass was placed on the sides of the specimen so the sealant would not leak out of the sides, and the beam specimen was adjusted to have a 1.0-mm crack between the two pieces. The edge of the table was locked on two sides to create a tight fit that would not allow the concrete specimen to move.

The sealants have a coverage rate of approximately 100 square feet per gallon so 89 mL of the sealants were prepared. They were all mixed using their respective manufacturer's ratio, and the recommended mixing time was used at a temperature of

20ºC. TK-2415 was the first sealant used; it was mixed in a disposable cup with the initiator and promoter using a glass stirring rod. The sealant was poured over the crack and the excess was forced into the crack using a squeegee. It was found that the sealant was flowing completely through the crack out the bottom of the specimen and onto the plastic drop cloth beneath the specimen.

The specimen was removed from the table once the sealant hardened in the crack and a new one was placed on the table. Since the plexiglass did not work in containing the sealants, stucco tape was placed over the cracks on the sides and bottom of the specimen. Kwik Bond was the next sealant applied to the specimen used because the TK-2415 had poor results on the first specimen. TK-2415 appeared to evaporate off the surface, making it difficult to tell where it flowed and more difficult to come up with a solution to contain the sealants. A crack width of 0.6 mm was set, and 89 mL of Kwik Bond were poured over the crack until the sealant could no longer flow into the crack due to polymerization. This process was repeated with a crack width of 1.0 mm and it was found that the Kwik Bond flowed out the bottom again. The beam specimen was removed once the sealant polymerized fully.

Because the sealant was still flowing out even with the stucco tape, DAP Flexible Clear Sealant was placed over the cracks on the sides and bottom and allowed to set for 15 minutes. Another beam specimen was placed on the table and set to a crack width of 0.2 mm, and 89 mL of Kwik Bond were poured over the crack until the sealant could no longer flow into the crack due to polymerization. The specimen was removed, and another beam specimen was placed onto the table with a crack width of 1.0 mm. Kwik Bond was used again to determine if the DAP sealant would hold the Kwik Bond in the

specimen. The mixture amount was doubled to ensure there was enough sealant to fill the crack if the sealant was contained in the specimen, so an amount of 177 mL of Kwik Bond were used. It still flowed all the way through and pooled on the plastic drop cloth. The specimen was removed, and another specimen was placed onto the table.

The DAP sealant was allowed to cure overnight to increase the chance of containing the sealants within the cracks. Stucco tape was placed over the cracks as well. The crack on the beam specimen was placed to a width of 0.8 mm, and 355 mL of Kwik Bond were mixed. The mixture amount was double again to ensure an adequate amount of sealant. The Kwik Bond was poured over the crack but still flowed completely through the crack and onto the plastic drop cloth. The specimen was removed, and another one was placed onto the table and set to a crack width of 0.4 mm. An amount of 177 mL of Kwik Bond was mixed and poured onto the crack until the sealant could no longer flow through the crack. The specimen was removed, and a new one was placed onto the table.

A crack width of 0.4 mm was set, and 177 mL of TK-2415 was poured over the crack until the sealant could no longer flow through the crack. It was noted that some sealant was pooling at the bottom on the plastic drop cloth. This process was repeated with the TK-2415 with a crack width of 0.2 mm. Because the TK-2415 was not being contained within the crack in the concrete specimen and it showed the ability to flow completely through the crack width, the TK-2415 was not tested on crack widths larger than 0.4 mm.

The next specimen was set with a crack ranging from 0.1 mm to 0.2 mm and 88 mL of Transpo T70 was poured onto the crack. Once again though, the sealant flowed completely through the crack and out the bottom of the specimen. Therefore, tests with larger cracks were not performed.

A slab specimen was tested next. It was placed on the platform on its side, making it 61 cm tall. Stucco tape was used to seal the cracks on the sides and the bottom, and cargo straps were used to tighten the specimen to a desired crack width. A plastic drop cloth was placed under the cargo straps and concrete specimen to capture excess sealants. A crack width ranging from 0.2 mm to 0.8 mm was created by adjusting the two broken pieces with the cargo straps, and 89 mL of Kwik Bond were poured over the crack. It was found that the sealant flowed completely through the crack and onto the plastic drop cloth. Another slab specimen was tested using the TK-2110 at a crack width of 0.8 mm with the same set up as before, and 148 mL of the sealant were poured over the crack until it could no longer penetrate the crack. It was noted that the epoxy also flowed out the bottom of the crack. This same test was done on the TK-2110 for crack widths of 0.6 mm, 0.4 mm, and 0.2 mm.

Another slab specimen was set to a crack width of 0.2 mm, and 88 mL of Transpo T70 was mixed and poured over the crack. The sealant was poured until there was none left in the cup, and it was noted that it flowed through the crack and out the bottom, so tests with larger cracks were not performed.

The next slab specimen was set to a crack width of 0.2 mm, and 88 mL of TK-2415 were poured over the crack until the sealant no longer flowed through the crack. A crack width of 0.4 mm was tested next; since the sealant flowed out the bottom of the crack, tests were not conducted on larger cracks. The same crack widths were tested using Kwik Bond, but due to time constraints, a crack width of 0.6 mm was not tested. This concluded the tests done on the slab specimens.

Cold Weather Test

Four beam specimens were placed on the table and moved outside; the specimens remained outside overnight to determine how well the sealants would penetrate in cold weather. The temperature was -5.5ºC when the specimens were placed outside and reached a low of -9ºC overnight. The following morning after 14 hours outside, 88 mL of Transpo T70, TK-2415, and Kwik Bond were mixed and applied to crack widths of 0.2 mm, 0.4 mm, and 0.6 mm, respectively. Additionally, 148 mL of TK-2110 were mixed to be used with a crack width of 0.6 mm; the temperature at the time was 3ºC and windy. The sealants remained inside overnight and were mixed inside before being taken outside to be poured over their respective cracks until the sealants would no longer flow into the crack or the mixtures in the cup ran out. This concluded the tests done on the beam specimens.

Ponding Tests

Once the specimens were tested, duct tape was used to make a small reservoir over the cracks to contain a small amount of water such that the water would seep into the cracks. This ensured that if there was a loss of water, it was due to it flowing through the crack and not over the sides of the specimen. A mixture of ½ tablespoon of Keda Dye powder and 177 mL of water was stirred until the powder were mixed fully into the water (Figure 17). The dyed water was then poured over the cracks; if the water immediately drained into the crack, no more water was poured. If the water did not drain, a sufficient amount of water was poured into the reservoir until there was adequate water over the

crack. The water was allowed to sit for 15 hours; if there was any water left, it was cleaned up with absorbent pads.

Figure 17. Ponding Tests

The concrete specimens were then separated to evaluate how well the sealant penetrated the crack and, if possible, resisted water penetration. The beam specimens were separated with a hammer and chisel while the slab specimens were separated with a larger force, either from lifting with a hoist or placing the specimen on a pallet, placing a 4x4 piece of wood over the crack, and hitting it with a sledge hammer. The results of the sealant penetrations were noted and are discussed in the following chapter.

IV. Results and Analysis

This chapter discusses the results and analysis of the laboratory experiments conducted in the previous chapter. There was not a clear result regarding which sealant had the lowest viscosity as it varied based on the temperature, but the Transpo T70 and TK-2415 sealants had the lowest viscosities. Kwik Bond had the shortest gel time, then TK-2415, Transpo T70, and TK-2110, respectively. The results showed that Transpo T70 performed the best in regards to crack penetration but, due to the sealants not being contained in the specimens, the ability for the sealants to resist water intrusion was undetermined. The TK-2110 appeared to form the stronger bond with the concrete as there were more breaks outside the initial crack when specimens were re-cracked.

Viscosity Tests

Table 6 shows the viscosity results recorded after performing tests on the neat monomer. For graphs of specific tests, refer to Appendix C. The results showed that the Kwik Bond had a higher viscosity than the other sealants; however, from visual inspection, the Kwik Bond flowed more easily when poured out of the container at a temperature of 20^{o}C than the TK-2110 epoxy, which may indicate that the Kwik Bond has better wettability. The wettability or surface tensions of the sealants might be a more important factor than viscosity when it comes to a sealant's ability to penetrate a crack. If there is a high surface tension, then the sealants might have a harder time penetrating a crack. Further research is suggested in this area to better understand the relationship between sealants and the cracks they are penetrating. As expected, the other high

molecular weight methacrylates had a much lower viscosity and the viscosity was affected by temperature changes. The sealants did not have similar values of viscosity changes based on temperature changes. The Transpo T70 had the smallest change in viscosity over this range, and the Kwik Bond had the largest change.

Table 8. Neat Monomer Viscosity Tests Summarization

Sealant	Temperature (ºC)	Average Viscosity (cps)	Viscosity Delta (cps)	Delta (%)
Kwik Bond HMWM	35	142	2672	1981
	25	475		
	15	1350		
	5	2814		
Transpo T70 HWMW	35	18	46	355
	25	26		
	15	39		
	5	64		
TK-2415 HMWM	35	6	161.1	2576
	25	34		
	15	167		
	5	152		
TK-2110 Epoxy	35	70	919	1413
	25	145		
	15	339		
	5	989		

* Delta was calculated by subtracting the highest viscosity found by the lowest.

The viscosity values shown in Table 6 are different than those provided by the manufacturers since they were obtained using different tests. The technical sheets for the HMWMs all state a viscosity of less than 25 cps, and the technical sheet for the epoxy states a viscosity of 124 cps. The tests performed in this research involved a much

slower rotation than the ASTM tests the manufacturers performed. Manufacturers usually use ASTM D2196, which involves a rotational viscometer instead of a cone and plate rheometer. The shear ramp tests show that all the sealants, except for the Transpo T70, were shear sensitive; their viscosities decreased as the shear increased. The largest changes in viscosity occurred at shear rates less than 1 sec^{-1}. This is important because it means that the rate at which the sealant flows through a crack will change; in other words, the viscosity of the sealants as they flow through a crack is unknown. If the sealants experience shear rates less than 1 sec^{-1}, the viscosities could vary greatly from what is expected. Even though a manufacturer provides viscosity data, it may not be indicative of how the sealant flows through a crack. As the concrete tests show, the sealants performed differently even though the manufacturers' data provides the same viscosities for the HMWMs. Further research into viscosities in relation to crack widths is needed to fully understand this relationship.

Table 7 shows the viscosity results for the sealants after polymerization began (i.e., after the catalyst was added). These viscosity tests were not conducted at 20ºC, which was the temperature of the laboratory used for testing the concrete specimens. The viscosity results in the row of 20ºC were interpolated using the results from 25ºC and 15ºC. The viscosity of the catalyzed resin compared to the neat monomer changed in different ways and magnitudes. For example, at 25ºC, catalyzed Kwik Bond was seven times lower than neat monomer, catalyzed T-70 was 70% higher than neat monomer, TK-2415 was 2.8 times lower than neat monomer, and TK-2110 was 23 cps higher. This change is a function of the viscosity of the catalyst and the amount added.

Table 9. Catalyzed Sealant Viscosity Tests Summarization

Sealant	Temperature (Cº)	Average Viscosity (cps)	Viscosity Delta (cps)**	Viscosity (%)
Kwik Bond HMWM	25	66	1989	3113
	20*	519		
	15	975		
	5	2055		
Transpo T70 HMWM	25	44	49	211
	20*	52		
	15	60		
	5	93		
TK-2415 HMWM	25	12	379	3258
	20*	81		
	15	150		
	5	391		
TK-2110 Epoxy	25	168	622	470
	20*	292		
	15	415		
	5	790		

* Results were interpolated

** Delta was calculated by subtracting the highest viscosity found by the lowest.

The catalyzed test results were similar to the neat monomer test results: Kwik Bond had the highest viscosities except at 25ºC, temperature had an effect on the viscosities, and Transpo T70 had the smallest viscosity change with temperature while Kwik Bond had the highest. There were also differences in the effect of shear rate compared to pure monomer results. For catalyzed resins, Kwik Bond, Transpo T-70, and TK-2415 exhibited shear-thinning behavior at 25ºC, while TK-2110 behaved relatively Newtonian (no significant shear rate dependence over the range tested). Another observation was

that the viscosities of Transpo T-70 and TK-2415 were essentially constant at each temperature over the course of the 2-minute isothermal hold. The viscosity of TK-2110 increased by 20-35% under the same conditions, presumably from the curing reaction. The viscosity of Kwik Bond was constant or slightly decreased. A decrease in viscosity could be caused by time-dependent shear-thinning behavior. The main result taken from this section is that the catalyzed Transpo T-70 and TK-2415 exhibited the lowest and most stable viscosity of the four products over the range tested.

However, the addition of the initiator and promoter had different effects on the viscosity. The results suggest that this difference, among all the other differences among the sealants such as viscosity and viscosity delta, is because of the different chemical makeups of the neat monomers. All three HMWMs used the same initiator, cumyl hydroperoxide, and the TK-2415 and Kwik Bond appeared to use the same promoter. The chemical makeup of the promoters was not given; however, they had similar color and odor. The only difference is the neat monomer and the reaction that occurs after the monomer is polymerized, further proving that all HMWMs are different and that no single HMWM is the appropriate solution for all cracks. Different situations will call for different HWMWs.

Gel Times/Pot Life

Table 8 shows the gel times for each sealant at 24ºC. Sample size was 50 mL except for TK-2110, which was 100 mL approximately. Kwik Bond and TK-2415 exhibited snap, or rapid, polymerizations where the viscosity increased exponentially in a short period of time, thus causing the sealant to harden quickly. This is typical for redox-initiated chain type polymerizations of vinyl type monomers such as HMWM. These

rapid polymerizations caused extreme heat and smoke to come from the sealant, to the point where it melted the plastic containers. In normal use, the resin is catalyzed and used immediately in a fashion that spreads out the liquid over a large surface; therefore, over-heating is not a problem. Transpo T70 and TK-2110 exhibited a more gradual viscosity increase; this was expected for TK-2110 since the epoxy cures by step (slow) polymerization in which a gradual increase in viscosity build is typical. Transpo T70 was a redox-initiated chain polymerization, which means that a retarder was likely included in that initiator system to slow the reaction down and make it appear more like a step polymerization. Additionally, the times between gel and hardening were larger than the Kwik Bond and TK-2415, which is also characteristics of step type polymerization. When the mixture ratios were changed, no matter which component was changed, the gel times always increased. This was expected for the conditions of reducing initiator, reducing promoter, and changing the epoxy Part A/Part B ratios. However, increasing the initiator or promoter concentrations was expected to significantly reduce pot life. This result remains unexplained. Another observation during the gel time tests was that larger sample volumes produced a shorter gel time. For example, while performing the concrete tests, 148 mL of epoxy cured after about 25 minutes, accompanied by smoking and intense heat. This effect is commonly experienced in polymerizations and is attributed to poor heat transfer. The curing reaction produces heat which accumulates more in larger samples (lower surface area-to-volume ratio), thus leading to higher temperatures and faster reactions.

Table 10. Gel Times

Sealant	Approximate Gel Time (min)	Approximate Harden Time (min)
Kwik Bond	20	22
Transpo T70	75	105
TK-2415	25	27
TK-2110	150	210

Concrete Penetration Tests

Tables 8 and 9 show the results of the concrete penetration tests. The beam specimens had Teflon tape placed in them so the cracks inside the specimens were very smooth and straight, compared with the cracks of the slab specimens which were rough and jagged due to the natural breaking. This did not appear to have any effect on how well the sealants penetrated the cracks. The distance the sealants traveled through the crack in the beam specimens were both farther and shorter relative to the same crack widths in the slab specimens. The sealants for the slab specimens did not have shallower penetrations relative to the beam specimens, while some experiments had deeper penetrations than the beam specimens.

Table 11. Beam Specimen Penetration Results

Crack Width (mm)	Sealant	Max Penetration Depth Achieved (cm)	Majority Penetration Depth Achieved (cm)*
0.2	TK-2415	61	2
	Kwik Bond	28	3
	Transpo T70	61	61
	Transpo T70 C	61	61
	TK-2110	Not Tested	-
0.4	TK-2415	61	20
	TK-2415 C	61	30
	Kwik Bond	40	2
	Transpo T70	Not Tested	-
	TK-2110	Not Tested	-
0.6	TK-2415	Not Tested	-
	Kwik Bond	61	Unable to tell
	Kwik Bond C	61	61
	Transpo T70	Not Tested	-
	TK-2110	61	61
	TK-2110 C	61	61
0.8	TK-2415	Not Tested	
	Kwik Bond	61	61
	Transpo T70	Not Tested	-
	TK-2110	Not Tested	-
1.0	TK-2415	61	61
	Kwik Bond	61	61
	Transpo T70	Not Tested	-
	TK-2110	Not Tested	-

* The point where 75% of the sealant reached.

Table 12. Slab Specimen Penetration Results

Crack Width (mm)	Sealant	Max Penetration Depth Achieved (cm)	Majority Penetration Depth Achieved (cm)*
0.2-0.25	TK-2415	31	20
	Kwik Bond	29	16
	Transpo T70	61	61
	TK-2110	18	12
0.4	TK-2415	61	61
	Kwik Bond	50	10
	Transpo T70	Not Tested	-
	TK-2110	58	26
0.6	TK-2415	Not Tested	-
	Kwik Bond	Not Tested	-
	Transpo T70	Not Tested	-
	TK-2110	61	61
0.8	TK-2415	Not Tested	-
	Kwik Bond	Not Tested	-
	Transpo T70	Not Tested	-
	TK-2110	61	61

* The point where 75% of the sealant reached.

The TK-2415 flowed into all crack widths, but struggled at 0.2 mm. It flowed more easily into 0.4-mm-wide cracks, but due to the quick polymerization, would begin to slow around 10 minutes after mixing. After 20 to 25 minutes, the sealant would be too viscous to continue to flow, quickly curing a few minutes after that point. A 1.0-mm crack was first tested with TK-2415; since the monomer flowed completely through the crack, a 0.4-mm crack specimen was tested next. Since the TK-2415 still reached the bottom of the crack, the 0.6-mm crack specimen was not tested. The water flowed through all the specimens except the 0.4-mm-wide beam specimen; in the 0.4-mm specimen, the sealant appeared to cure at the surface, so little water was able to penetrate. In the cold weather

test, the sealant was still able to flow completely through the cracks and reach the bottom. It also appeared to evaporate after about 24 hours (bottom left of Figure 30 in the Appendix), thereby making it difficult to tell where the sealant flowed to in the specimens.

The Kwik Bond flowed in all cracks but had difficulty flowing completely through the 0.2- and 0.4-mm cracks; however, it flowed completely through the specimens with 0.6-mm and wider cracks. For the 0.2-, 0.4-, and 0.6-mm specimens, the sealant pooled at the top and no water was able to penetrate in those areas. For the 0.8- and 1.0-mm cracks, both the sealant and water flowed completely through the crack. In the cold weather test, the sealant flowed completely through the crack but became too viscous at a faster rate than for the higher temperature tests. When the specimens were re-cracked, some of the new cracks went through the concrete and not through the original cracks.

The Transpo T70 flowed completely through a crack that was 0.1 to 0.2 mm wide for the beam specimen and 0.25 mm wide for the slab specimen. Because it flowed easily in these cracks, larger crack widths were not tested. The cold weather test provided the same results, and the sealant easily flowed to the bottom of the specimen. The cold weather did not affect the viscosity like the other sealants. In the laboratory tests measuring viscosity, temperature changes affected the Transpo T70 viscosity the least. When re-cracked, the new crack occurred in the concrete in a small portion. Both the sealant and water flowed completely through the cracks in all specimens. The TK-2110 epoxy flowed into all the cracks regardless of width but only reached the full depth in the 0.6- and 0.8-mm crack widths, while penetrating nearly full depth on the 0.4-mm width specimens. The sealant was only tested at the 0.6-mm width on the beam specimens due

to a lack of specimens. For the cold weather test, the sealant (TK-2110 epoxy) flowed completely through the specimen and out the bottom; however, like the TK-2415 and Kwik Bond, it became viscous more quickly than usual, so a smaller amount was used. The water was not able to penetrate areas where the sealant had been applied in all specimens, except the one with the 0.8-mm crack; this was because the sealant flowed completely through and out the bottom of this specimen. In re-cracking of all the specimens except the 0.8-mm width specimen, there were many locations where new cracks occurred outside the sealant and inside the concrete. The TK-2110 had more locations like this than any other sealant.

While all sealants were able to penetrate 0.2-mm crack widths, the Transpo T70 performed the best in regard to crack penetration. Due to its longer curing time and lower viscosity, it was easily able to penetrate cracks as small as 0.1 mm completely. It also performed the best in the cold weather test, with no reduction in performance. The TK-2110 appeared to form the strongest bond with the concrete because more new cracks developed in the concrete as opposed to the other sealants. However, because in many cases the sealant flowed completely out of the specimen, it is difficult to make that judgement. The TK-2415 penetrated the second best, the Kwik Bond the third, and the TK-2110 the least.

V. Conclusion

The following chapter summarizes the results, both from the literature review and the tests performed during the research. It also discusses recommendations for further evaluation of whether or not high molecular weight methacrylate (HMWM) is the right solution for use in concrete airfield pavements.

Results Summary

Based on the literature review and tests conducted during this research, HMWM is considered a viable option to repair shrinkage cracks in concrete airfield pavement. HMWM has shown the potential to flow into very fine cracks, as small as 0.1 mm in width, restore the structural integrity of the concrete, and prevent water and chemical intrusion. In regard to crack penetration, the Transpo T70 performed the best, easily penetrating 0.1-mm cracks; the TK-2415 and TK-2110 performed the second best, penetrating 0.4-mm cracks; and Kwik Bond penetrating 0.6-mm cracks. These results are most likely directly related to the viscosity of these sealants. The ranking from lowest to highest viscosity at given temperature is consistent: Transpo T70, TK-2415, TK-2110, and Kwik Bond. As expected, temperature affected the viscosity; the colder the temperature, the higher the viscosity. This was shown in the laboratory tests with the rheometer as well as tests conducted outside. The viscosity for Transpo T70 was affected the least and still penetrated a 0.2-mm crack with ease. The other sealants were more affected, and became too viscous at lower temperatures.

In the areas where the sealant was able to collect in the cracks, the TK-2110 appeared to have the strongest bond with concrete. There were more breaks outside of the initial

crack when specimens were re-cracked. Transpo T70 and Kwik Bond also had breaks outside of the initial crack but not to the extent of the TK-2110. The TK-2415 did not form a strong bond with the concrete, as it looked like it evaporated after 24 hours on many of the specimens. The TK-2415 and Kwik Bond experienced snap polymerizations in which they cured within 30 minutes, going from a gelled state to a hardened state in a few minutes with intense heat. Transpo T70 and TK-2110 experienced more gradual polymerizations, taking much longer to cure, over 90 minutes, and going from a gelled state to a hardened state over a long period of time. However, when more of the TK-2110 was mixed together, it cured within 30 minutes with intense heat, thereby proving that the volume of sealant being mixed can have a large impact on the gel time.

The ability for the sealants to prevent water from penetrating the cracks was not able to be determined in this research because the sealants could not be contained; they flowed completely through the cracks in the specimens and could not form a complete bond with the concrete. There were some areas that looked promising, mainly with the Kwik Bond. When the Kwik Bond pooled on the specimen surface because it could no longer penetrate the crack, water could not enter those areas. Additionally, in the specimen with the 0.8-mm crack, the Kwik Bond pooled at the bottom of the crack specimen and it could easily be seen that the water was collecting above the Kwik Bond at the bottom as well. Even though the majority of the sealants were not contained, and thus were not able remain in the crack, there was signs that the sealants could form a strong bond with the concrete. These results, among others found in the literature review, show that the sealants have the ability to bond to concrete and not allow any water penetration.

Recommendations

It is difficult to define the requirements for HMWM as a crack sealer. The chemical makeup of the HMWM will determine the characteristics of the sealant such as strength, viscosity, durability, and elongation. This research has shown that three different HMWMs exhibited different results when it came to penetration. Based on published data, Transpo T70 does not have properties that set it apart from the other two HMWMs, yet it outperformed them when it came to penetrating very fine cracks. This may have to do with the fact that it had a lower viscosity at the temperature when the tests were performed or because it had smaller viscosity changes due to shear change. A viscosity of 50 cps or lower is recommended for cracks less than 0.4 mm, and a viscosity of 50 cps or greater is recommended for cracks greater than 0.4 mm.

Because of the HMWM's ability to penetrate fine cracks, it should be determined whether the crack being treated is a full-depth crack over a porous subbase. If this is the case, the HMWM will probably flow through the crack and into the subbase, similar to what was experienced on some bridge decks when the HMWM flowed out the bottom. However, this is usually not the case as pavement tends to rest on a soil that seals the bottom. Additionally, shrinkage cracks are usually only a few centimeters in depth, so leakage should not be an issue. As long as the cracks are confined and there is no place for the HMWM to exit, the sealant should fill up the crack and seal it.

Gel time should be considered as well. When pouring the TK-2415 and Kwik Bond, they gelled before all of the mixture could be applied. When they struggled penetrating into cracks, they had to be worked constantly and then slowly seeped into the cracks. This took time and eventually the mixture gelled up. The TK-2110 also struggled up to a

point because it was slowly becoming more viscous, so not all of the mixture could be poured into the crack. The Transpo T70 performed the best because it remained a liquid past 60 minutes, thereby allowing for ample time to penetrate the crack. For cracks finer than 0.6 mm, gel times of greater than 60 minutes is recommended. However, for cracks greater than 0.6 mm, shorter gel times can be considered because the material is less likely to become too viscous before it can fully penetrate the crack. The literature repeatedly showed that the cracks must be dry and free of all debris or dirt. When the cracks are wet or contaminated, the sealants rarely bonded to the concrete, which resulted in poor performance. It is also recommended that the sealant be applied very early in the morning or late at night, when the temperature is at it coolest for the day

Strength is not as important when it comes to shrinkage cracks because they tend to be relatively small in width. Because of this, the higher the elongation percentage the better. It is more important for the sealant to move with the expansion and contraction of the concrete than it is to restore the strength. The higher strength sealants tend to be less flexible than the weaker ones. However, the wider the cracks, the more important strength and durability become over elongation. If the treatment for shrinkage cracks is no longer the concern, then strength should be looked at more closely.

The ultimate goal of the sealant in very fine shrinkage cracks is to seal the crack. This is accomplished when the sealant can penetrate the crack, bond to the concrete, and keep out water and other chemicals. From the literature and the laboratory testing accomplished in this research, HMWM has shown to do all of that, and is recommended as a treatment option.

This research was not able to test how HMWMs will withstand the stresses encountered on an airfield pavement. Therefore, to further evaluate HMWMs, field studies are recommended in which different HMWMs are applied over an airfield pavement. A study to examine the relationship between shear thinning properties and crack widths is recommended as well. For deeper pavements, the viscosity is more important since the sealant will have farther to travel. If the shear rates are lower, such as under 1 sec^{-1}, the viscosity differs greatly from data obtained from manufacturers. The relationship between surface tension and crack penetration would also be an area to research further. The surface tension of a sealant might have a larger effect on crack penetration than viscosity.

Appendix A. Concrete Mix Design

Martin Marietta

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Colorado Springs, Colorado 80905

Office: (719) 473-3100

Dispatch: (719) 638-8000

CONCRETE MIXTURE DESIGN REPORT

MM Mixture ID#: Date A4482
Mix Reported : Class/ Use: 5/8/2017

4000 PSI; General Exterior Concrete

Material	Amount / Cubic Yard	Source / Type	ASTM Std.
Cement	564 lbs	Type 1-11 LA	C 150
Coarse Aggregate*	1740 lbs	Martin Marietta #57/67	C 33
Fine Aggregate*	1315 lbs	Martin Marietta WCS	C 33
Water (30.47 gal.)	253.8 lbs	Muncipal	C 94
Air Entraining Agent**	** oz	Sika AEA-14	C 260
Water Reducer**	** oz	Sika Plastocrete 161	C494
Water Reducer**	•• oz	Sika Sikament 686	C494

*Aggregate masses determined in SSD condition.

•• AEA adjustments at plant and on site may be required to achieve proper air entrainment. Air adjustments may be made with either liquid or Fritz air entrainment and Perfin.

Mix proportions may be adjusted in accordance with ACI 301-2008 section 4.2.3.6.

**Admixture dosages may be adjusted based on varying environmental and/or jobsite conditions.

Specified Physical Properties

Compressive Strength:	**4000** psi (Min)
Air Content:	**5.0-8.0** % (Range)
Slump: (w/cm)	
Ratio: Unit	**3.00-5.00** in. (Range)
Weight:	**0.45** (Max)
	143.44 (lbs)

Appendix B. Key Terms

The definition of key terms are as follows:

Curing Agent: an organic monomer, considered part "B" in an epoxy resin system. The agent initiates the chemical reaction with the epoxy to form a polymer.

Epoxy: an organic monomer with an epoxy group, considered part "A" in an epoxy resin system.

High molecular weight methacrylate (HMWM): an acrylic based organic monomer, closely related to methyl methacrylate but contains a higher molecular weight.

Initiator: an organic monomer (usually a peroxide) that induces a chemical reaction with HMWM. The initiator is mixed with the HMWM to initiate a chemical reaction that forms a polymer.

Methyl Methacrylate (MMA): an acrylic based organic monomer, $C_5H_8O_2$, and a thermoplastic.

Monomer: Any reactive molecule that forms a polymer when they bond together in a chain reaction. One major family is compounds that contain one or more carbon-to-carbon double bond such as methacrylate. Another major family are pair of compounds that have mutually reactive groups, such as epoxy and amine compounds. (Klosterman 2018).

Monomer System: The mixture of all the monomers. For HMWM, it is the HMWM monomer, the initiator, and the promoter. For epoxy, it is part A and part B.

Neat Resin: a pure or mixture of monomers, such as the methacrylate monomer part of the HMWM or part A.

Polymerization: the reaction of monomers to form a linear, branched, or crosslinked polymer (Klosterman 2018).

Polymethyl methacrylate: Methyl methacrylate that has gone through polymerization, going from a monomer to a polymer.

Pot life: For this research, the time between mixing of the components and the time when the material cannot be worked and is unable to flow.

Promoter: an organic monomer that aids in the chemical reaction of the HMWM and the initiator. Usually a promoter enables the peroxide to form free radicals at a faster rate, thereby allowing polymerization to be initiated at room temperature or below.

Thermoplastic: a polymer that can be molded to specific shapes because it softens when it heats up. It is comprised of linear or branched polymer structure.

Volatile Organic Compounds (VOC): any organic compound that evaporates quickly at room temperature and causes reactions that are not good for the environment. (This leads to products with high levels of VOCs that are prohibited (Jiang 2008).)

Appendix C. Viscosity Test Graphs

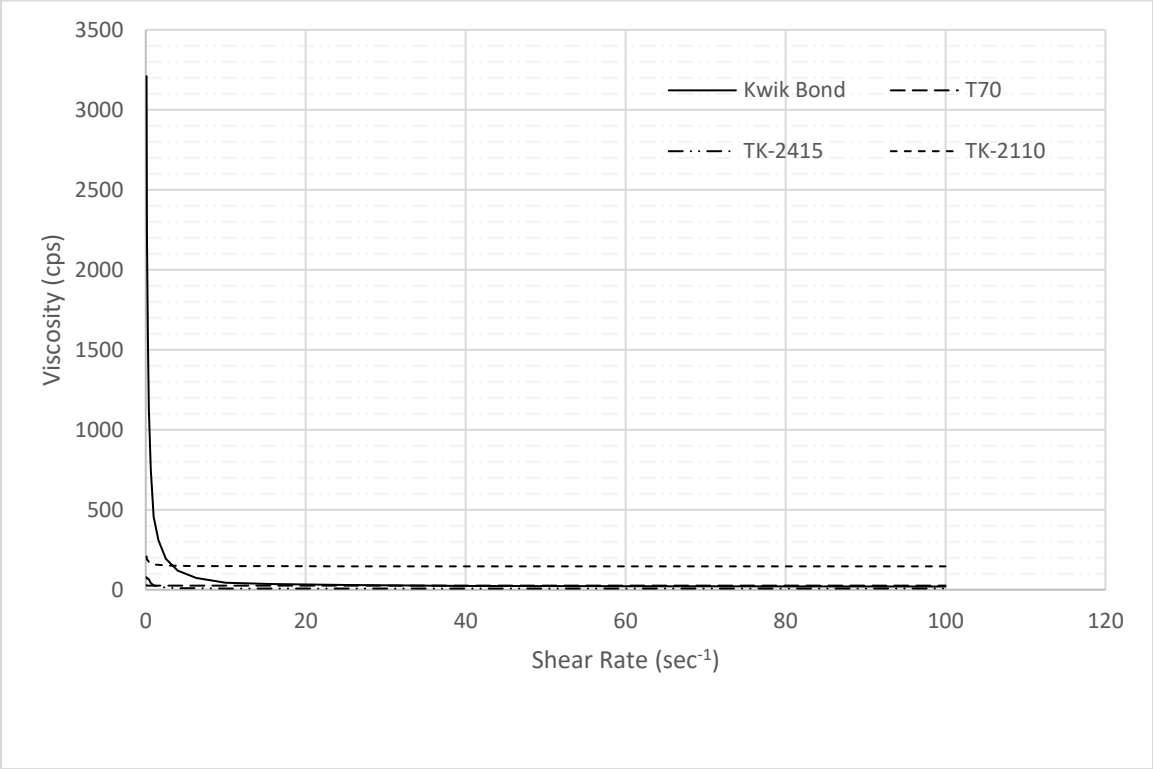

Figure 18. Neat Monomer Viscosity Tests - Shear Ramp at 25 ºC

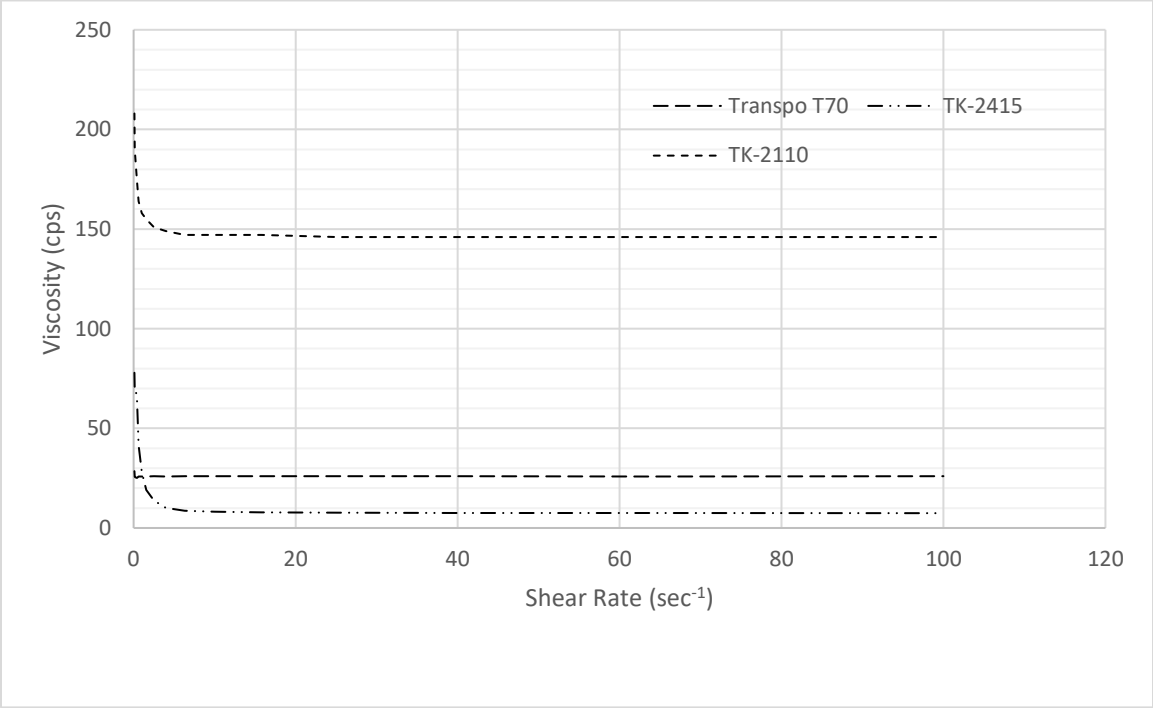

Figure 19. Neat Monomer Viscosity Tests - Shear Ramp at 25 ºC (excluding Kwik Bond)

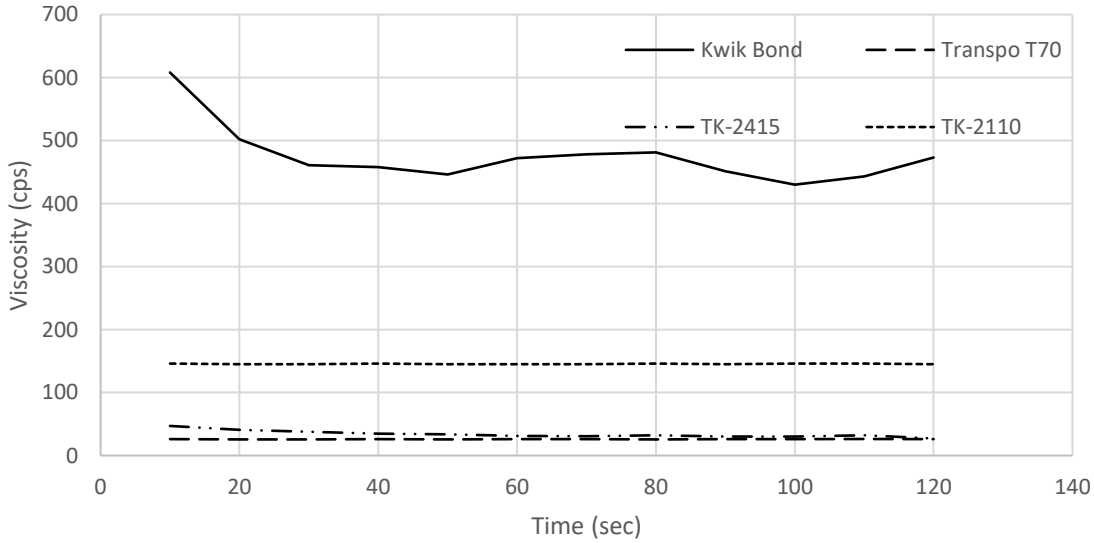

Figure 20. Neat Monomer Viscosity Tests – Constant Shear Rate (1.0 sec^{-1}) at 25 ºC

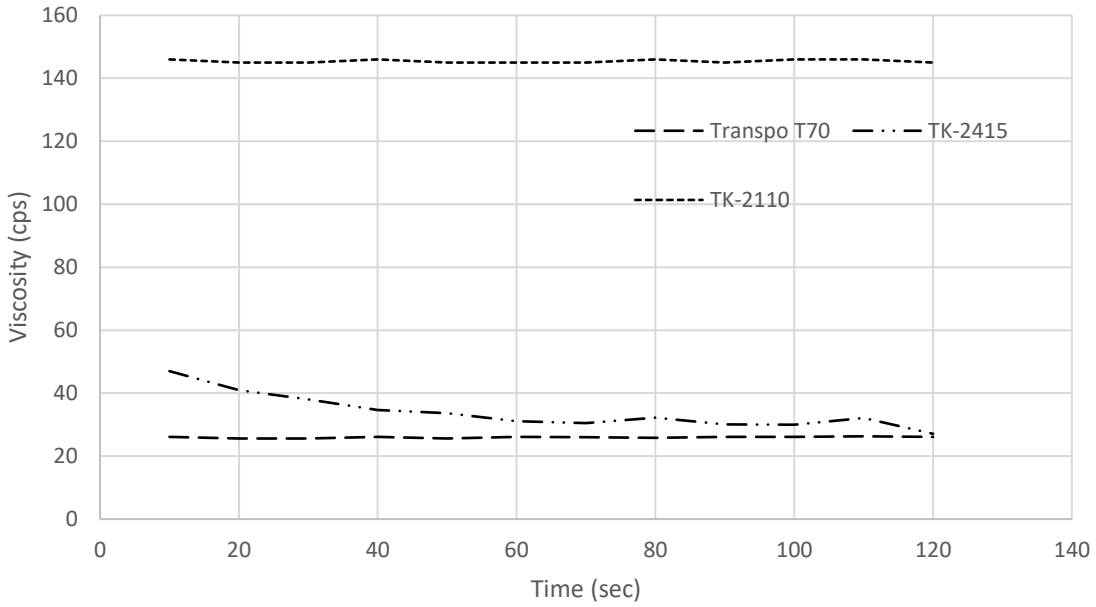

Figure 21. Neat Monomer Viscosity Tests - Constant Shear Rate (1.0 sec^{-1})f at 25 ºC (excluding Kwik Bond)

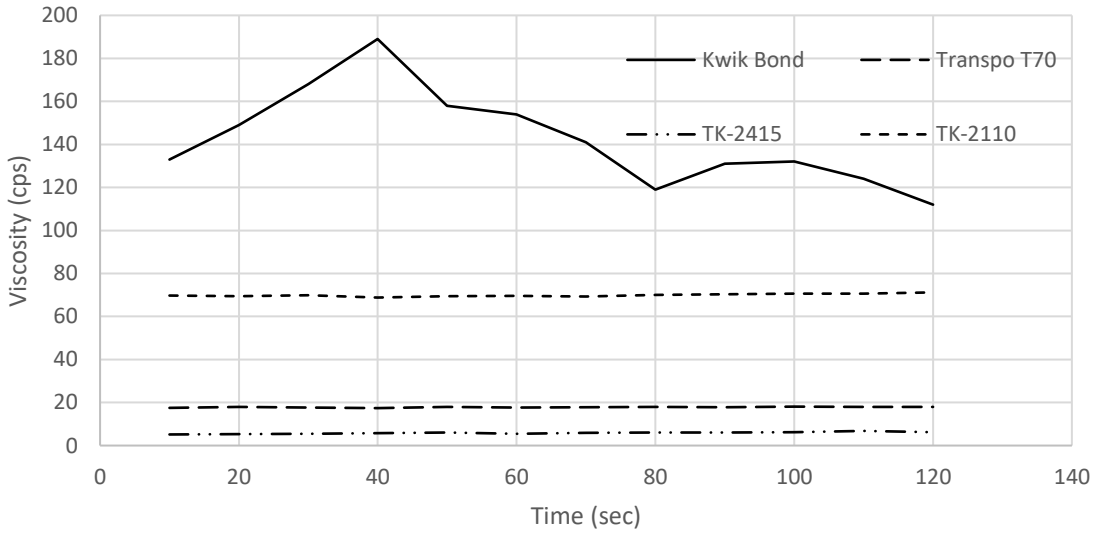

Figure 22. Neat Monomer Viscosity Tests - Constant Shear at 35 ºC

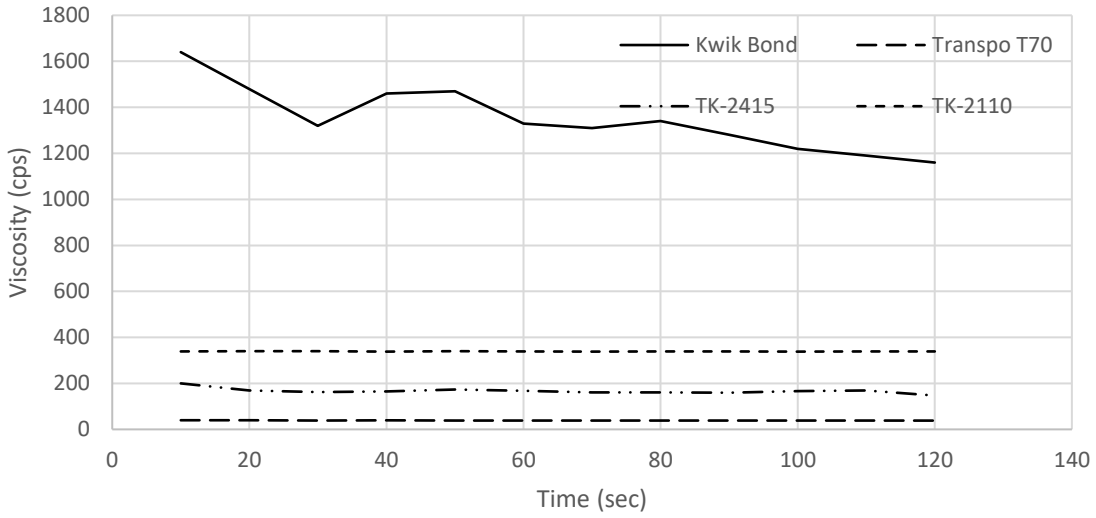

Figure 23. Neat Monomer Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 15 ºC

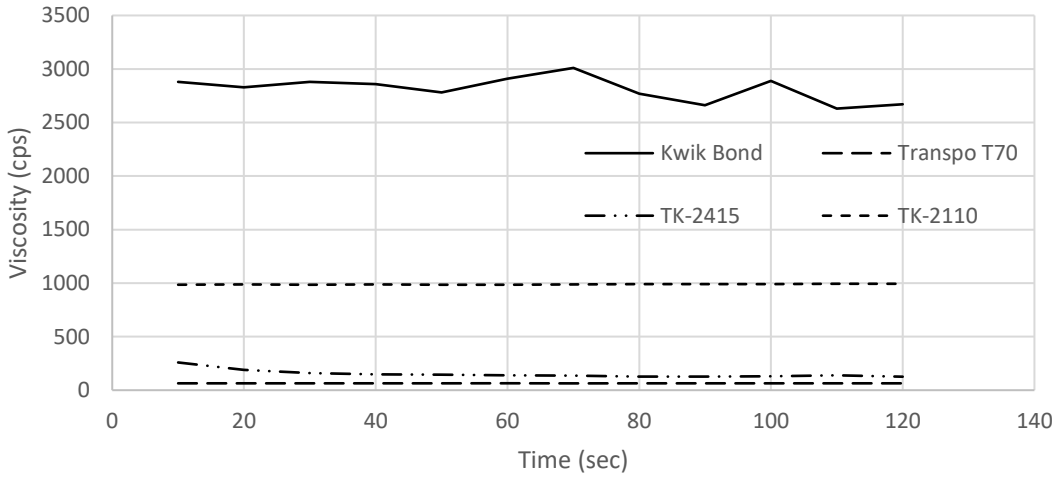

Figure 24. Neat Monomer Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 5 ºC

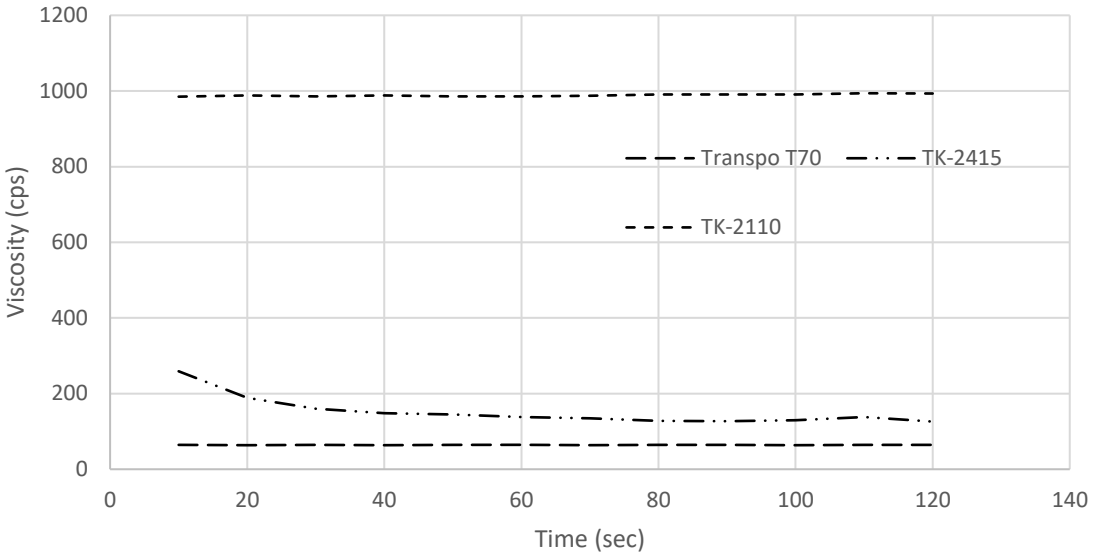

Figure 26. Neat Monomer Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 5 ºC (excluding Kwik Bond)

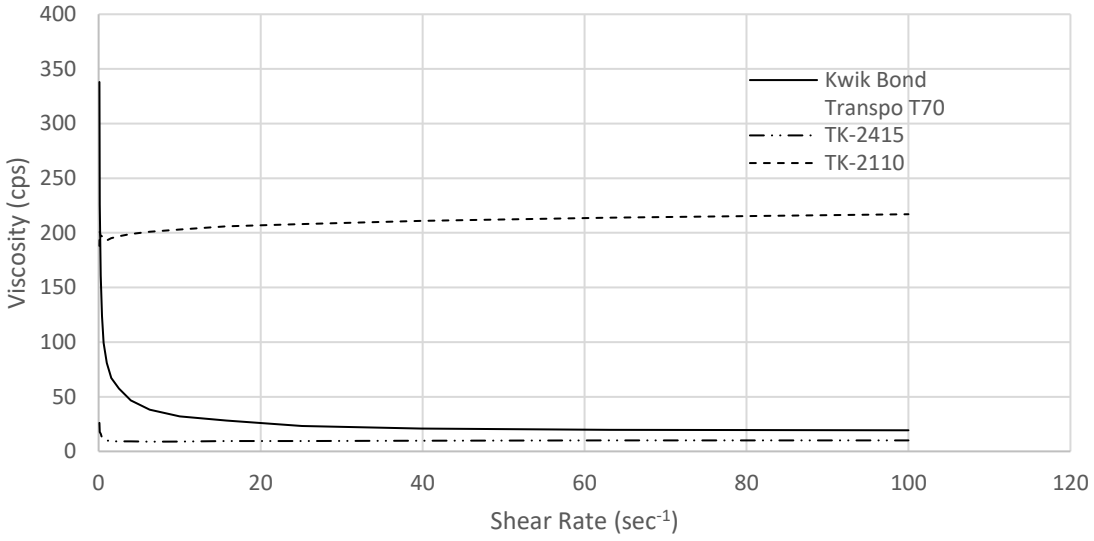

Figure 25. Sealant Viscosity Tests - Shear Ramp at 25 ºC

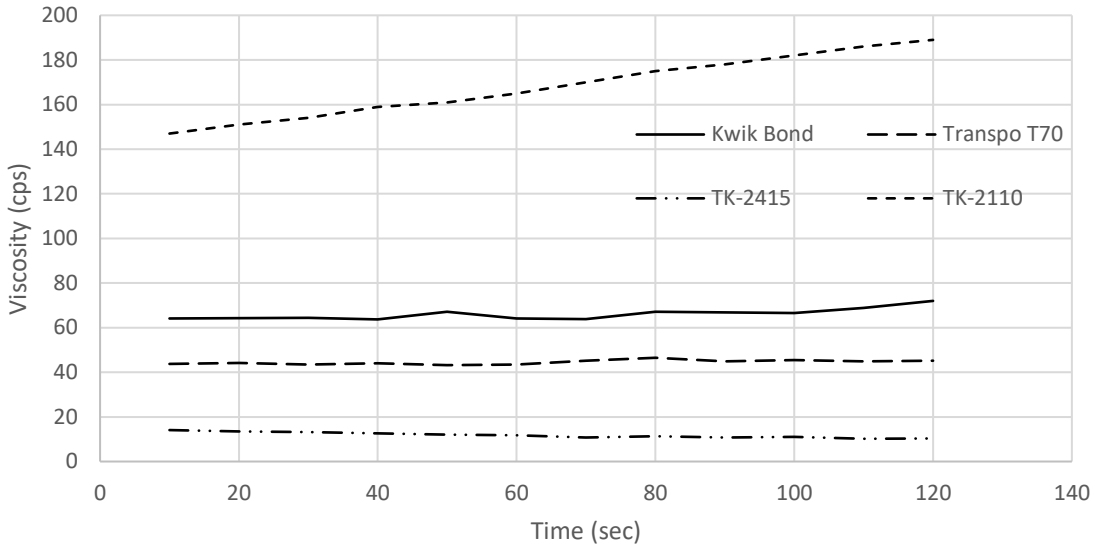

Figure 27. Sealant Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 25 ºC

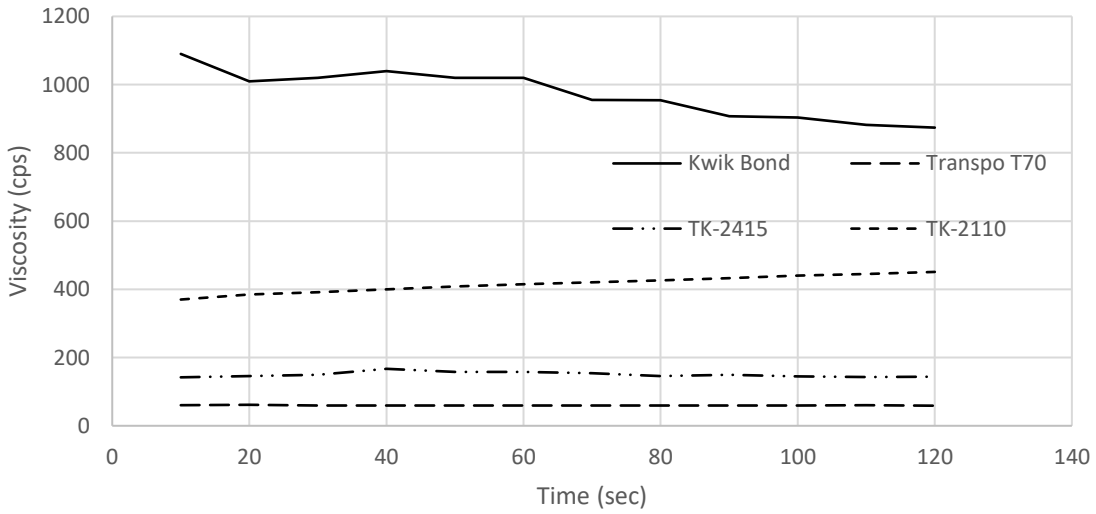

Figure 28. Sealant Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 15 ºC

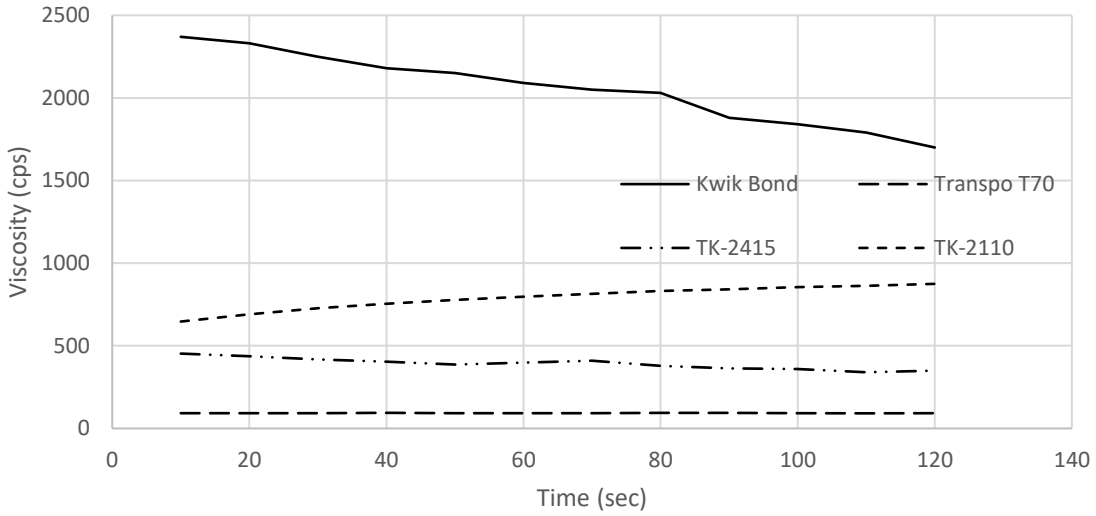

Figure 29. Sealant Viscosity Tests - Constant Shear Rate (1.0 sec^{-1}) at 5 ºC

Appendix D. Specimen Penetration Results

Table 13. Beam Specimen Results

Number	Sealant	Crack Width (mm)	Sealant Result	Ponding Result
13	TK-2415	0.2	Very small amount flowed into crack, with a small portion reaching full 61 cm, appears to have flowed through wider portion of crack. No other sealant appeared to penetrate. Sealant cured before all could be poured into crack.	Sealant evaporated in 24 hours so ponding test could not be conducted.
14	TK-2415	0.4	Some sealant flowed into the crack, reaching the bottom of the specimen. The majority flowed to 20 cm. The sealant cured before all could be poured in.	Water appeared to flow through in some parts but did not penetrate in some areas.
15	TK-2415	0.4	Failed specimen	
1	TK-2415	1	Sealant flowed completely through and pooled at the bottom.	Water flowed completely through because the sealant flowed through as well.
8	TK-2415 C	0.4	Flowed through 0.4 mm cracks, large portion appeared to flow approximately 30 cm but larger cracks were present which provided space to flow through.	Water flowed throughout the specimen but no sealant remained in specimen as the sealant flowed out.
4	Kwik Bond	0.2	Very little flowed into crack. Small portion went to about 28 cm but majority that entered stayed around surface, < 3 cm. Sealant cured before all could be poured in.	Water did not penetrate into crack due to buildup of sealant on surface.
16	Kwik Bond	0.4	Little flowed into crack, some went to around 40 cm while most stayed around 2 cm. Sealant cured before all could be poured in.	Water appeared to not flow through the areas with the sealant, only areas where the sealant was not present.
2	Kwik Bond	0.6	Most went into the crack. Some went to bottom of specimen and pooled up. Difficult to determine where majority stopped. Sealant cured before all could be poured in.	Water did not penetrate the crack due to buildup of sealant on surface.

Table 14. Beam Specimen Results (continued)

Number	Sealant	Crack Width (mm)	Sealant Result	Ponding Result
6	Kwik Bond	0.8	Sealant flowed completely through and pooled at bottom of the specimen for about 12 cm. Some sealant did flow out of the specimen. All sealant was used before it cured.	Water flowed through the crack but did not flow through areas where sealant pooled.
3	Kwik Bond	1	Sealant flowed completely through and pooled at the bottom.	Water flowed completely through because the sealant flowed through as well.
5	Kwik Bond	1	Sealant flowed completely through and pooled at the bottom.	Water flowed completely through because the sealant flowed through as well.
10	Kwik Bond C	0.6	Sealant flowed completely through and pooled at the bottom. Due to the cold weather, material became too viscous after 5 minutes and could no longer flow.	Water did not penetrate the crack where the sealant was present, only areas it was not.
12	T70	0.1-0.2	Sealant flowed completed through and pooled at the bottom. All sealant was used before curing occurred.	Water flowed completely through because the sealant flowed through as well.
9	T70 C	0.2	Sealant flowed completed through and pooled at the bottom. All sealant was used before curing occurred.	Water flowed completely through because the sealant flowed through as well.
7	TK-2110	0.6	Sealant flowed completely through and pooled at bottom of the specimen and out of the specimen. The sealant became too viscous to continue to flow into crack.	Water did not penetrate into crack where sealant was, only areas it was not.
11	TK-2110 C	0.6	Sealant flowed completely through but, due to the cold weather, became too viscous and could no longer flow through the crack.	Water only penetrated the larger crack widths where the epoxy did not cure onto the surface.

Table 15. Slab Specimen Results

Number	Sealant	Crack Width (mm)	Sealant Result	Ponding Result
6	TK-2415	0.2	Some flowed through the crack, reaching 31 cm; most that flowed into crack appeared to stop at 20 cm. Sealant cured before all could be poured into crack.	Water flowed into crack and areas where the sealant was present. Appears sealant that was present evaporated off concrete.
7	TK-2415	0.4	Most flowed through the crack, flowing out of the bottom of the specimen. Sealant cured before all could be poured into crack.	Water appeared to barely flow where sealant was present.
8	Kwik Bond	0.2	Very little sealant flowed into crack, only reaching 29 cm at the deepest. Most only flowed 16 cm. When re-cracked, specimen did re-crack in some section outside of the sealant and into the concrete. Sealant cured before all could be poured into crack.	Water did not appear to penetrate the areas where the sealant was present.
9	Kwik Bond	0.4	Some flowed into the crack, reaching 50 cm, most that flowed into crack only reached 10 cm. When re-cracked, specimen did re-crack in some section outside of the sealant and into the concrete. Sealant cured before all could be poured into the crack.	Water did not appear to penetrate the areas where the sealant was present.
15	T70	0.25	Sealant flowed completely through the crack and pooled at the bottom. When re-cracked, some of the crack occurred in the concrete and not in the initial crack. All sealant was used before curing occurred.	Water flowed completely through because the sealant flowed through as well.
13	TK-2110	0.2	Very little sealant flowed into crack, reaching 18 cm at its deepest. The majority of the sealant appears to have flowed to around 12 cm. Specimen did re-crack almost completely outside the sealant and into the concrete. Sealant became too viscous before all sealant could be poured into the crack.	Very little water, if any, flowed into the areas where sealer was present. It appeared to only flow where the sealer was not present.

Table 16. Slab Specimen Results (continued)

Number	Sealant	Crack Width (mm)	Sealant Result	Ponding Result
12	TK-2110	0.4	Some sealant flowed into the crack, reaching around 58 cm. The majority appears to stop around 26 cm. When re-cracked, some of the crack occurred in the concrete and not in the initial crack. The sealant became too viscous before all sealant could be poured.	Water did not appear to penetrate the areas where the sealant was present.
11	TK-2110	0.6	Some sealant flowed into the crack, reaching the full depth of the specimen. No sealant pooled at the bottom and most of it went the whole length. When re-cracked, some of the crack occurred in the concrete and not in the initial crack. The sealant became too viscous before all sealant could be poured.	Water did not appear to penetrate the areas where the sealant was present.
14	TK-2110	0.8	Most of sealant flowed into the crack, pooling at the bottom of the specimen. The sealant became too viscous before all sealant could be poured.	Water flowed completely through because the sealant flowed through as well.
1	Not Tested			
2	Not Tested			
3	Not Tested			
4	Not Tested			
5	Not Tested			
10	Not Tested			
16	Not Tested			

Appendix E. Laboratory Test Pictures

Figure 30. TK-2415 Beam Specimen at 0.2 mm

Figure 31. TK-2415 Beam Specimen at 0.4 mm

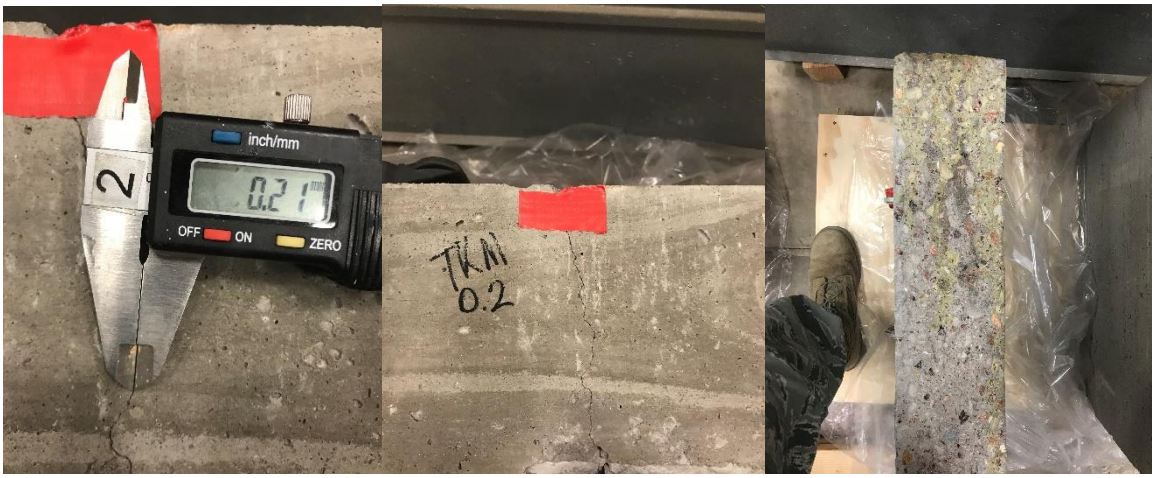

Figure 32. TK-2415 Slab Specimen at 0.2 mm

Figure 33. TK-2415 Slab Specimen at 0.4 mm

Figure 34. TK-2415 Cold Weather Test

Figure 35. Kwik Bond Beam Specimen at 0.2 mm

Figure 36. Kwik Bond Beam Specimen at 0.4 mm

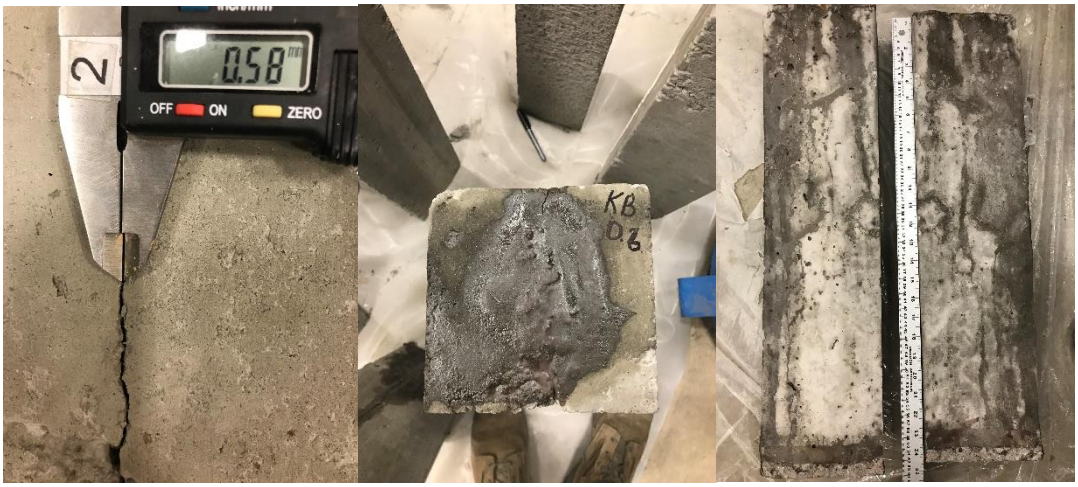

Figure 37. Kwik Bond Beam Specimen at 0.6 mm

Figure 38. Kwik Bond Beam Specimen at 0.8 mm

Figure 39. Kwik Bond Beam Specimen at 1.0 mm

Figure 40. Kwik Bond Slab Specimen at 0.2 mm

Figure 41. Kwik Bond Slab Specimen at 0.4 mm

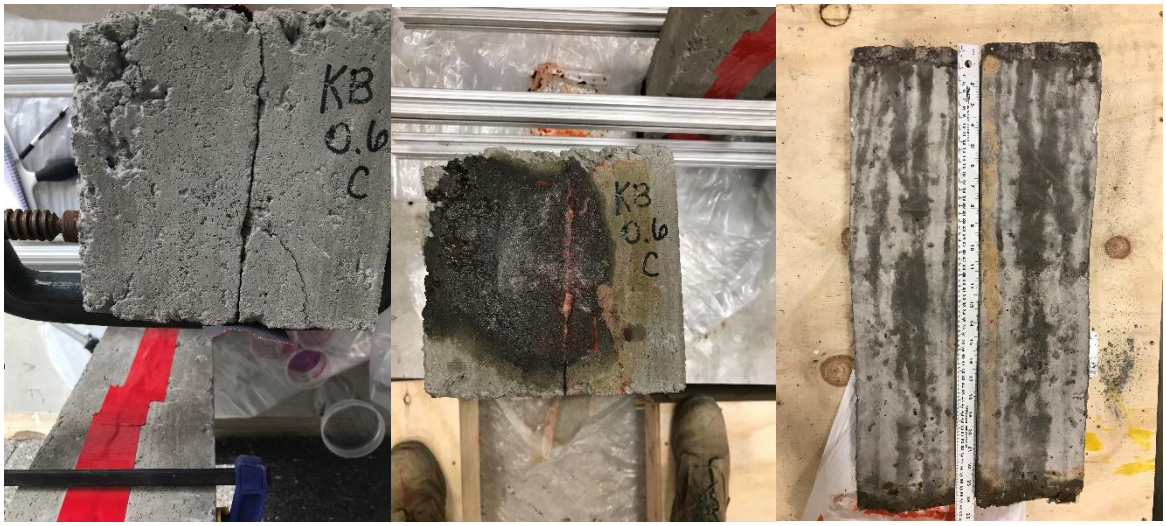

Figure 42. Kwik Bond Cold Weather Test

Figure 43. Transpo T70 Beam Specimen at 0.1-0.2 mm

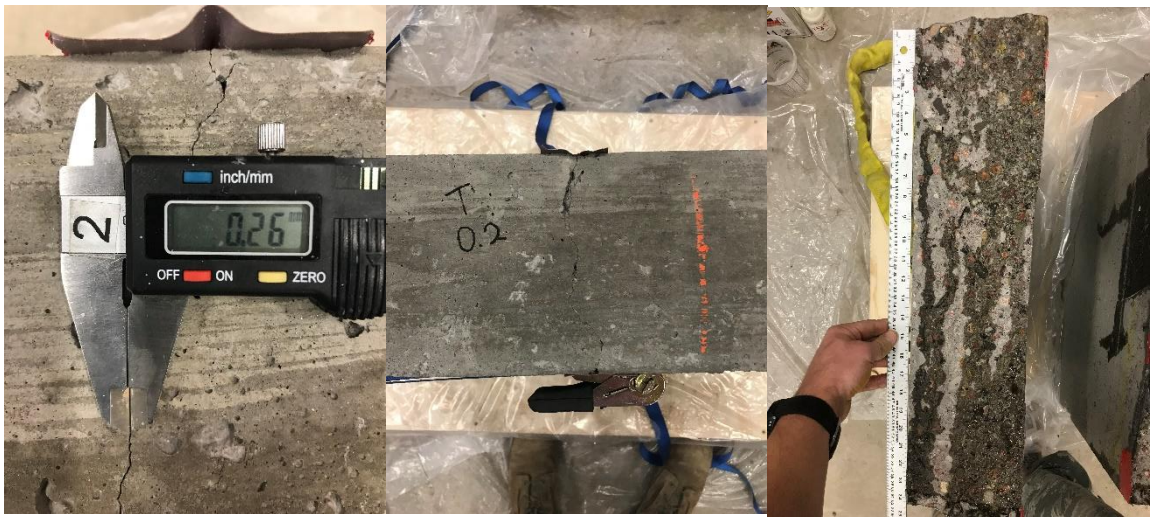

Figure 44. Transpo T70 Slab Specimen at 0.25 mm

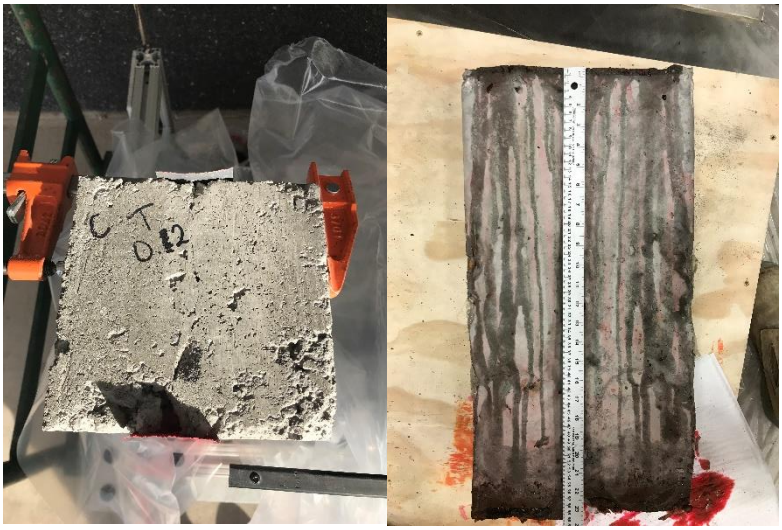

Figure 45. Transpo T70 Cold Weather Test

Figure 46. TK-2110 Beam Specimen at 0.6 mm

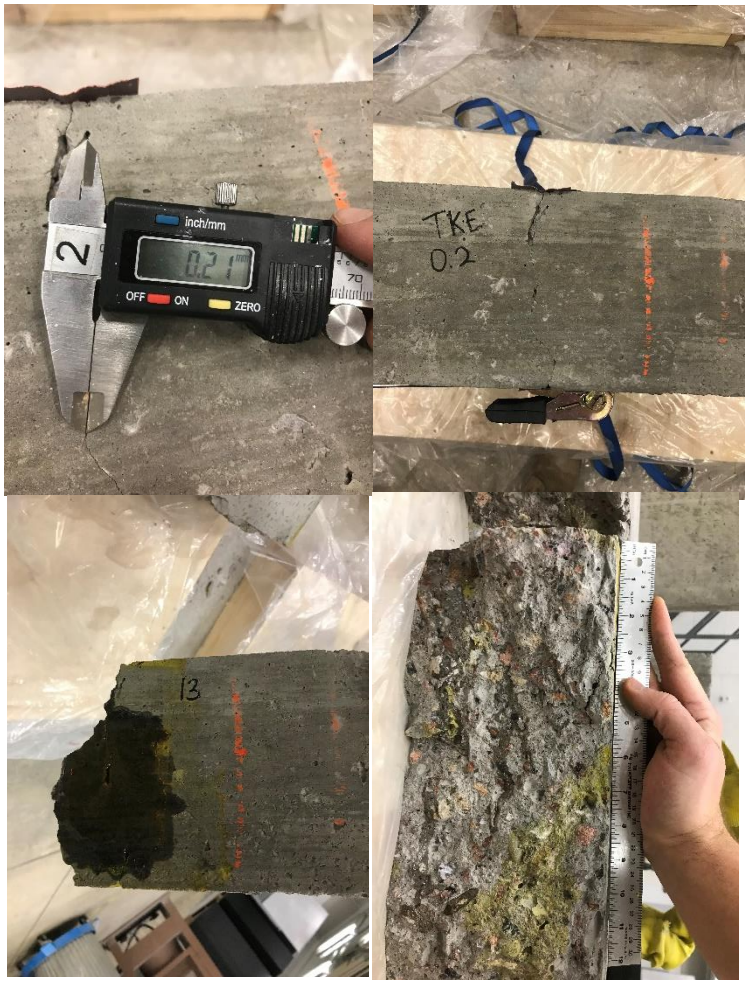

Figure 47. TK-2110 Slab Specimen at 0.2 mm

Figure 48. TK-2110 Slab Specimen at 0.4 mm

Figure 49. TK-2110 Slab Specimen at 0.6 mm

Figure 50. TK-2110 Slab Specimen at 0.8 mm

Figure 51. TK-2110 Cold Weather Test

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14. ABSTRACT

Air Force policy dictates that only epoxy can be used as a treatment option for shrinkage cracks in concrete airfield pavement. However, since epoxy is not ideal for shrinkage cracks, this research focuses on the evaluation of high molecular weight methacrylate (HMWM) as a treatment option. Laboratory experiments were performed on four sealants to determine whether they could penetrate a crack 24 inches deep, bond to the concrete, and resist water intrusion. Three HMWMs and one epoxy were assessed. The four sealers were applied to 32 concrete specimens with crack widths varying from 0.2 mm to 1 mm. Dyed water was poured onto the surface and allowed to sit before the concrete specimens were re-broken, at which point the specimens were evaluated to determine where, if any, water penetrated the crack. Beam specimens were also tested in cold weather, with similar results. Evaluating the ability for the sealants to bond to the concrete and resist water intrusion was not accomplished because the sealants could not be contained in the specimens. Despite this, the laboratory results suggest that HMWM would be a viable option to treat shrinkage cracks in concrete airfield pavement, which is consistent with the literature.

15. SUBJECT TERMS

High molecular weight methacrylate; concrete; shrinkage crack treatment; airfield pavement; sealant

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